Ecological and Economic Optimisation of Biogas Plants

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MPhil

2012

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A thesis submitted in partial fulfilment
of the requirements of De Montfort University
for the degree of Master of Philosophy (MPhil)

January 2012

Institute of Energy and Sustainable Development
De Montfort University Leicester

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Abstract

This research project provides guidelines for biogas operators, planners and manufacturers with tangible suggestions for improvements in ecology and economy.

In order to achieve this, 10 biogas plants in Bavaria (Germany) with an electric capacity from 30 kW_{el} to 560 kW_{el} are thoroughly analysed and evaluated.

Within the project, first a widespread data analysis is made. The analysis contains e.g. measuring the parasitic electric energy or detecting methane leaks. Also the operational log of the biogas plants is analysed with respect to feedstock, down times, labour times and maintenance.

The next step of this project is the evaluation of the generated data. For this purpose, key performance indicators are used to carry out a benchmark and error analysis.

Knowing the problems of biogas plants, finally leads to the development of optimisation concepts. Eight approaches are generated to improve the plants` ecology and economy.

The project proves that ecology and economy can very well go together. By reducing methane emissions of biogas plants more biogas can be used in the CHP-Unit. This causes a better ecologic situation by reducing greenhouse gas emissions. Moreover, less feedstock has to be put into biogas plants while having the same output. Using less feedstock means less current costs.

Acknowledgements

This research project was carried out at the *Institute of Energy and Sustainable Development* at *De Montfort University Leicester* in cooperation with the *Centre of Excellence for Renewable Energy Research* at *Ingolstadt University of Applied Sciences*.

I would like to thank my supervising team namely Prof. Vic Hanby and Prof. Wilfried Zörner for the initiation of this research work, for their excellent support and guidance as well as for their revision of this thesis.

Furthermore, I would like to give special thanks to the German *Federal Ministry for the Environment, Nature Conservation and Nuclear Safety*, in particular to Uwe Holzhammer. He was always willing to give support when needed.

Moreover, I am very grateful to the students and colleagues who accompanied me during the years at the *Centre of Excellence for Renewable Energy Research*, especially to Georg Häring, Holger Müller, Sebastian Brandmayr, Hermann Riess and Dr. Christoph Trinkl. They gave me support when ever needed and made the university much more than just a place to work.

Finally, I would like to thank my parents Maximilian and Adelheid as well as my brother Hannes for their enduring support and their encouragement throughout the work.

I declare that the content of this submission is my own work. The contents of the work have not been submitted for any other academic or professional award. I acknowledge that this thesis is submitted according to the conditions laid down in the regulations. Furthermore, I declare that the work was carried out as part of the course for which I was registered. I draw attention to any relevant considerations of rights of third parties.

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Abbreviations

a	Year
BY	Biogas plant in Bavaria
CCM	Corn-Cob-Mix
CH_4	Methane
CHP-Unit	Combined Heat and Power Unit
CO_2	Carbon dioxide
GHG	Greenhouse gas
H_2S	Hydrogen sulphide
NH_3	Ammonia
O_2	Oxygen
ppm	Parts per million

Symbols

AcOH	Acetic acid	[g/l]
$A_{leakage}$	Area of biogas leak	[m²]
B_R	Volume load	$[kg_{oDM}/m^3_{active\ digester} \cdot d]$
BTA	Butyric acid	[g/l]
CA	Caproic acid	[g/l]
D_B	Depreciation for the building	€
DM	Dry matter	[g/kg]
D_T	Depreciation for technical equipment	€
EC	Electric conductivity	[mS/cm]
$E_{el,\ component,\ d}$	Daily electric energy consumption of a component	$[kWh_{el}/d]$
$E_{el,\ consumption,\ d}$	Daily electric energy consumption	$[kWh_{el}/d]$
$E_{el,\ gross,\ a}$	Annual gross electric energy production	$[kWh_{el}/a]$
$E_{el,\ gross,\ d}$	Daily gross electric energy production	$[kWh_{el}/d]$
$E_{el,\ gross,\ literature,\ a}$	Annual gross electric energy production, theoretical	$[kWh_{el}/a]$
$E_{feeding\ system,\ d}$	Daily feeding system electric energy consumption	$[kWh_{el}/d]$
$E_{methane,\ d}$	Daily needed energy of methane	[kWh/d]
$E_{spec.,\ d\ \frac{stirring}{active\ digester}}$	Specific stirring electric energy consumption per 100 m³ active digester volume	$[kWh_{el}/100m^3_{active\ digester} \cdot d]$
$E_{spec.\ desulphurisation}$	Specific desulphurisation electric energy consumption	$[(kWh_{el}/d)/(Nm^3/h)]$
$E_{spec.\frac{feeding\ system}{t_{FM}}}$	Specific feeding system electric energy consumption per t added feedstock (without slurry)	$[kWh_{el}/t_{FM}]$

$E_{spec.\frac{stirring}{t_{FM}}}$	Specific stirring electric energy consumption per t added feedstock	$[kWh_{el}/t_{FM}]$
$\sum E_{stirrer, d}$	Daily total stirring electric energy consumption	$[kWh_{el}/d]$
f	Debt-financing	%
F_B	Financing cost for the building	€
FM	Fresh mass/Feedstock	$[t_{FM}]$
F_T	Financing cost for technical equipment	€
HAc-Eq.	Acetic acid equivalent	$[g\ HAc_{eq.}/l]$
$H_{L, methane, norm}$	Calorific value of methane	$[kWh/Nm^3]$
HRT	Hydraulic retention time	[d]
i	Interest rate	%
iBTA	Iso butyric acid	g/l
I_G	Investment for the building	€
iPTA	Iso valeric acid	g/l
I_T	Investment for technical equipment	€
M_B	Maintenance cost for building	€
$\dot{m}_{FM, d}$	Daily added feedstock (with or without slurry)	$[t_{FM}/d]$
$\dot{m}_{oDM, d}$	Daily added oDM	$[kg_{oDM}/d]$
M_T	Maintenance cost for technical equipment	€
NH_4^+-N	Ammonia nitrogen	[g/l]
oDM	Organic dry matter	[g/kg]
$P_{B, CHP}$	Electric capacity of CHP-Unit	$[kW_{el}]$
$P_{el, component}$	Effective power of a component	$[kW_{el}]$
$P_{el, desulphurisation}$	Electric power desulphurisation	$[kW_{el}]$
PPA	Propionic acid	[g/l]

PTA	Valeric acid	[g/l]
SCE	Substrate conversion efficiency	[%]
$t_{component, d}$	Daily runtime of a component	[h/d]
$t_{desulphurisation, h}$	Runtime of desulphurisation	[h/d]
TIC	Total inorganic carbon	[g $HAc_{eq.}$/l]
$V_{active\ digester}$	Active digester volume	[$m^3_{active\ digester}$]
VOA	Volatile organic acid	[g $HAc_{eq.}$/l]
$\dot{V}_{biogas, h}$	Biogas volume flow	[Nm^3/h]
$\dot{V}_d$	Daily added substrate volume	[m^3/d]
$\dot{V}_{leakage}$	Leakage rate of biogas	[m^3/s]
$\dot{V}_{methane, d}$	Daily methane volume flow	[Nm^3/d]
ρ_{biogas}	Density of biogas	[kg/m^3]
Δp	Pressure difference between inside digester and atmosphere	[mbar]

1 Introduction

2008 was a difficult year for the German biogas sector. After a dramatic price increase for energy crops in the summer of 2007, the following autumn saw the beginning of discussions about the amendment of the German Renewable Energies Act (EEG). Every few years, this law, which regulates the compensation paid for electricity from renewable primary products, is reviewed.

The amendment in 2004 preceded a boom in the years 2004 to 2006 followed by a phase of stagnation in the biogas sector in the years 2007 and 2008. The demand for new production facilities fell to almost zero and biogas plant operators suffered from the dramatic price increase for energy crops. Some farmers were even forced to close down their biogas production facilities as a reaction to the lack of profit potential. The amendment to the EEG was introduced in 2009, and the economic situation of the biogas sector has since improved.

Incomplete and premature planning, low-quality construction work and a lack of operators' skill are still the major problems agricultural biogas plants are faced with (Sonnleitner and Zörner 2007). These problems directly interfere with the economic and ecological situation (Sonnleitner and Zörner 2008). Agricultural biogas production plants can pose an economic risk for biogas plant operators, i.e. the farmers. Furthermore, these facilities can contribute notable methane emissions to the atmosphere which prohibit a long-term environmentally friendly energy supply.

A research project supported by the *German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety* is carried out in order to improve the ecological and economic performance of agricultural biogas plants by generating guidelines for biogas operators, planners and manufacturers with tangible suggestions for improvements. In order to achieve this, 10 biogas plants in Bavaria (Germany) are thoroughly analysed and evaluated.

The aim of the thesis is to develop a systematic methodology to support recommendations for the economic and ecological improvement of biogas plants.

In order to meet this aim the study will address the following objectives:

A number of in-depth case studies will be carried out on a range of agricultural biogas plants.

A set of characteristics to support recommendations for improvements will be identified from the case studies and contemporary literature.

A multi-method approach will be adopted involving the monitoring and measurement of the case studies, interviews and questionnaires with operators and a systematic review of relevant current policy.

The first chapter of the thesis contains a literature review with regard to data-bases/monitoring projects, parasitic electric energy and greenhouse gas balances of bio-gas plants.

A widespread data analysis of the 10 selected biogas plants is carried out in the second chapter. The analysis considers a number of areas for comparison, such as the meas-urement of the parasitic electric energy, or the detection of methane leaks. The opera-tional log of the biogas plants is also analysed with respect to a number of categories including feedstock, down times, labour times and maintenance.

The next stage of the thesis is the evaluation of the generated data. For this purpose, key performance indicators are used to carry out a benchmark and error analysis.

The increased awareness of the problems biogas plants are faced with finally leads to the development of optimisation concepts. Eight approaches are generated to improve the ecology and economy of the plants:

1. Shortening the Distance between Silo and Feeding System
2. Improving Substrate Conversion by using Highly Efficient CHP-Units
3. Improving Substrate Conversion by Avoiding Biogas Leaks
4. Reducing Methane Emissions and Improving Substrate Conversion by Covering Residue Storage Tanks
5. Lowering Desulphurisation Electric Energy Consumption via Air Injection
6. Improving Heat Utilisation via a Structured Planning Approach
7. Improving Heat Utilisation through the Implementation of Heat Meters
8. Improving Utilisation of the CHP-Unit

2 Literature Review

There are currently several monitoring projects in which research was carried out on specific topics such as parasitic electric energy and methane emissions of biogas plants. These projects provide databases for comparison of biogas plants.

2.1 Databases and Monitoring Projects

In Fachagentur Nachwachsende Rohstoffe e.V. (2009c) biogas plants are analysed according to their efficiency, operational modes and reliability. In total 63 biogas plants are selected which have different system concepts, operational modes and feedstock. Data is recorded in several measurements over a period of one year and the biogas plants are finally compared with one another. Thus, parameters for the evaluation of the plants are defined.

First, the configuration of the biogas plant is analysed regarding the following components (excerpt):

- type of digester (vertical, horizontal, combination of both types),
- type of fermentation process (dry, wet),
- digestion temperature,
- digester volume,
- electric and thermal capacity of the CHP-Unit(s),
- type of gasholder,
- type of desulphurisation,
- specific active digester volume,
- specific gasholder volume,
- type of heat utilisation.

A further area for investigation is the operational mode of the biogas production process. Therefore, the following figures and values (excerpt) are defined and analysed:

- used feedstock (renewable raw materials, livestock slurry/manure)
- used renewable raw materials (maize silage, CCM, …),
- used livestock slurry/manure (cattle slurry, pig slurry, …),
- dry matter,
- organic dry matter,
- figures for the determination of the biological process,
- hydraulic retention time,

- composition of biogas (CH_4, CO_2, O_2, H_2S),
- biogas yield,
- methane yield,
- remaining biogas potential in the residue storage tank at different temperatures,
- CHP-Unit usage rate,
- electric output,
- amount of heat utilised,
- parasitic electric energy.

An economic evaluation of the investigated biogas plants is carried out in detail (excerpt) considering:

- investment for the biogas plants,
- investment for CHP-Unit(s),
- earnings per year (electricity, heat, fertilizer, …),
- expenditure per year (feedstock, parasitic electric energy, depreciation, …),
- profit,
- amortisation.

An ecological evaluation of the biogas plants is also included within this project. The following factors are examined (excerpt):

- farmland for cropping (meadow land, plough land),
- owned farmland for crop growing,
- transport distance for renewable raw materials (farmland to biogas plant).

This publication is a broad database in which figures for the analysis and comparison of biogas plants are described. Fachagentur Nachwachsende Rohstoffe e.V. (2009c), however, does not contain any suggestions to improve the biogas plants in ecology and economy; and furthermore, methane emissions caused by biogas leaks are not considered and greenhouse gas balance sheets are not included.

Another database for the evaluation of biogas plants in Germany can be found in Döhler et al. (2009a). Here, data from several publications and values for comparison are summarised. This publication gives detailed information about the dimensioning and operation of biogas plants. First, the essential components of biogas plants are described, then the feedstock, which can be used for the production of biogas, is examined. The biogas yield of specific substrates is shown. The biological process, utilisation of biogas, and finally an economic and ecological evaluation of biogas plants is documented. Also contained in this publication is a broad database with a large amount of cost data for both components and substrates. A weakness of this publication is the lack of suggestions for improvements. The ecological evaluation does not discuss methane emissions from leaks, and so there are no approaches for the reduction of methane losses from those leaks.

An analysis of the energetic efficiency of ten biogas plants in Bavaria is carried out in Effenberger et al. (2009). In this paper, the biogas production process is subdivided into the four groups: substrate supply, biogas production, biogas utilisation and digestate utilisation. Several figures for comparison are defined and finally the selected biogas plants are evaluated. Another topic within this paper is the measurement of the parasitic electric energy and greenhouse gas balances are also included. However, this paper does not contain suggestions to improve the efficiency of biogas plants.

In Bundesministerium für Verkehr, Innovation und Technologie (2008) the potential for the optimisation of biogas plants in Austria is described. The process steps and several components for the production of biogas are considered within this publication. These topics are subdivided into the potential for optimisation during the stages of project planning, construction and operation. Finally, the topics are rated according to their potential for optimisation and solutions are proposed. The suggested solutions do not contain specific figures (expenditures, earnings), but it is a thorough summary of topics with potential for optimisation.

2.2 Parasitic Electric Energy

In Dachs and Rehm (2006) 35 biogas plants are investigated. Figures for comparison are defined in order to evaluate the parasitic electric energy of each plant, and the main electric consumers of the biogas plant are described.

A collection of data from literature review, manufacturers` and biogas plant operators` information in addition to test measurements is presented in this publication. The parasitic electric energy of six biogas plants is measured in detail and compared to values from literature. The mean consumption varies between 5.8 % (literature) and 8.1 % (measurements). The aim of this project is the reduction of the parasitic electric energy through the suggestion of approaches to the plant operators. Due to the many influencing factors in the biogas production process, a reduction of the parasitic electric energy by such action as the reduction of the stirring interval, can have negative effects on the overall process. According to this publication, further research has to be carried out. The report is a useful guide to the measurement of parasitic electric energy of biogas plants, but it does not consider the negative effects of several of the suggested actions. Furthermore, the reduction of greenhouse gas emissions by lowering the parasitic electric energy is not taken into account.

The parasitic electric energy of biogas plants is further investigated in Effenberger et al. (2010). In this publication there is also particular focus on the parasitic electric energy consumption of both stirring and feeding system. The main electricity consumers of biogas plants are highlighted, and figures for comparison of the five biogas plants are defined. Finally, greenhouse gas emissions due to the purchased electricity and the potential for the reduction of these emissions are discussed. However, this publication lacks specific suggestions for improvements.

2.3 Greenhouse Gas Balance Sheet / Methane Emissions

A further focus of the literature review is the topic of methane emissions from biogas plants. The sustainable production and utilisation of biogas is described in a paper by Köppen and Reinhardt (2010), in which an analysis of the ecological effects of the production and utilisation of biogas and biomethane is carried out. Greenhouse gas balances are integrated for the production of electricity and heat from biogas. A comparison of different feedstock for biogas is also carried out with regard to its ecological effects. The various types of feedstock and the utilisation of biogas are evaluated and suggestions for improvements are presented. These suggestions, however, are not specific and do not propose estimates for investments, earnings and savings of greenhouse gas emissions. Furthermore, this paper does not consider leaks as an area of potential for the optimisation of biogas plants.

In Clemens et al. (2009) the greenhouse gas emissions from biogas plants are analysed. Sources of emissions from the storage of feedstock to the utilisation of digestate are identified. Possible sources of emissions are silage, feeding system, foil coverings, non-covered residue storage tanks, separators and CHP-Units. Further emissions are found at portholes and at agitators. The emissions from biogas plants are quantified and suggestions for the reduction of greenhouse gases are given, but this publication does not consider these emissions from an economic perspective.

Greenhouse gas balances of seven European biogas plants are also carried out in Niebaum et al. (2010), and the costs for reducing greenhouse gas emissions are addressed in this paper. Within this analysis, biogas plants with an electric capacity between 300 kW_{el} and 2,400 kW_{el} are considered. The loads and credits of the biogas production process are shown and compared with each other, and as a result, areas with potential for optimisation are suggested, such as the covering of residue storage tanks, the increased usage of organic manure/slurry and the increased utilisation of heat.

In Lansche and Müller (2011) the effects on climate due to the production of energy from biogas are discussed. The analysis of four biogas plants with an electric capacity from 50 kW_{el} to 2,000 kW_{el} shows that all biogas plants contribute to the protection of the climate, and the potential for optimisation is also identified.

2.4 Conclusions

The literature review can be summarised as follows. Research which is has already been done provides useful data about the current situation of biogas plants in Germany. Information concerning parasitic electric energy and greenhouse gas balances of biogas plants are also available, basic suggestions for improvements are outlined.

However, no specific approaches for the implementation of these suggestions are available, that consider biogas plants as an overall system, including the important processes before and after the plant itself. Furthermore, the combination of ecology and economy is not taken into account in any of the reviewed literature.

For these reasons, this thesis contributes to science by suggesting approaches for optimisation which show that ecology and economy can be improved simultaneously. The selected approaches are based on a thorough data analysis and evaluation, thus the specific suggestions for improvements are simple to be realised, low cost and quickly implementable in the context of the overall system of a biogas plant.

3 Data-Acquisition and -Analysis

3.1 Selection of Biogas Plants to be Investigated

To implement the investigation of typical biogas plants, the selection is based on several aspects including:

- electric capacity of CHP-Unit,
- type of engine,
- feedstock used,
- variation of manufacturers,
- type of digester.

Electric Capacity of CHP-Unit

In 2009 in Bavaria 1,691 biogas plants were in operation with an overall electric capacity of 424 MW_{el} (Figure 3.1). The mean electric capacity of each biogas plant in Bavaria was 251 kW_{el}, so in order to select representative biogas plants, the electric capacity of the investigated plants varies from 30 kW_{el} to 560 kW_{el}.

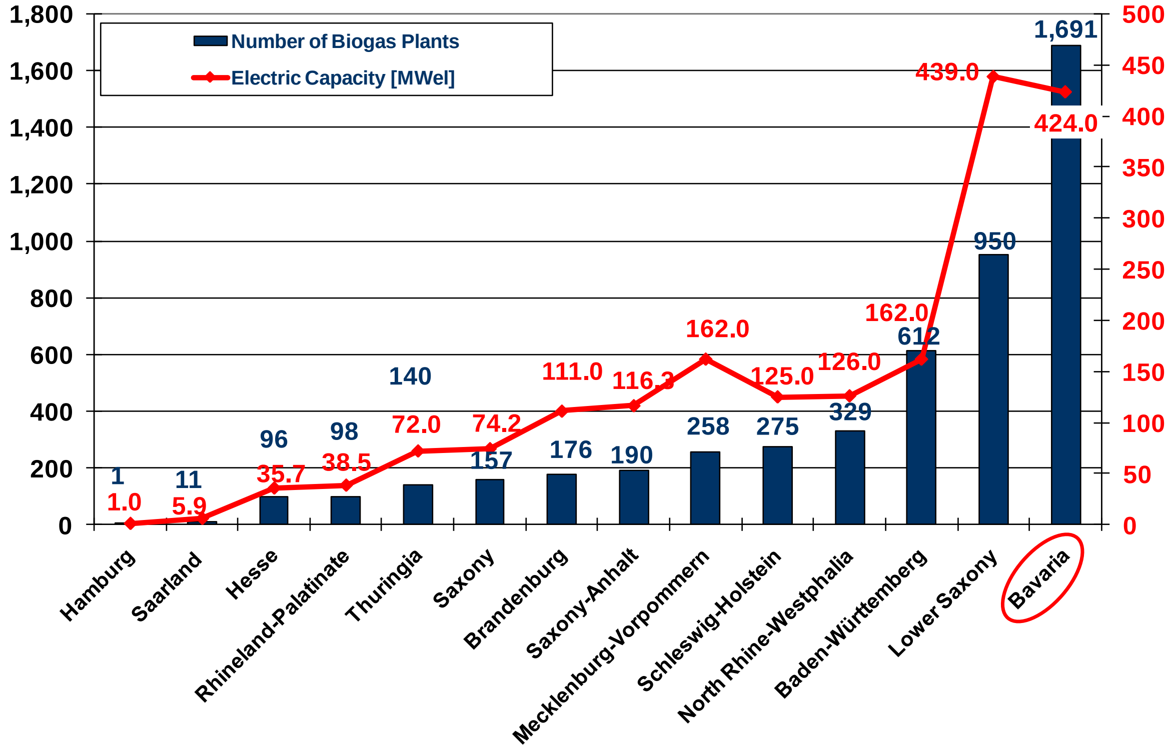


Figure 3.1: Electric capacity and number of biogas plants in Germany (Fachverband Biogas e.V. 2010)

Type of CHP-Unit

In Bavaria 72 % of the biogas utilisation via CHP-Units is carried out by gas engines. The other type of engines used are pilot injection engines (Röhling and Wild 2008). For this reason the selected biogas plants are equipped with a mix of gas and pilot injection CHP-Units.

Used Feedstock/Substrate

Figure 3.2 shows the substrates used in Germany. It is found that 37 % of the substrates are organic waste (such as cattle slurry) and 63 % are renewable raw materials (such as maize silage). With the exception of one biogas plant, all selected biogas plants use a mixture of renewable raw materials and organic waste.

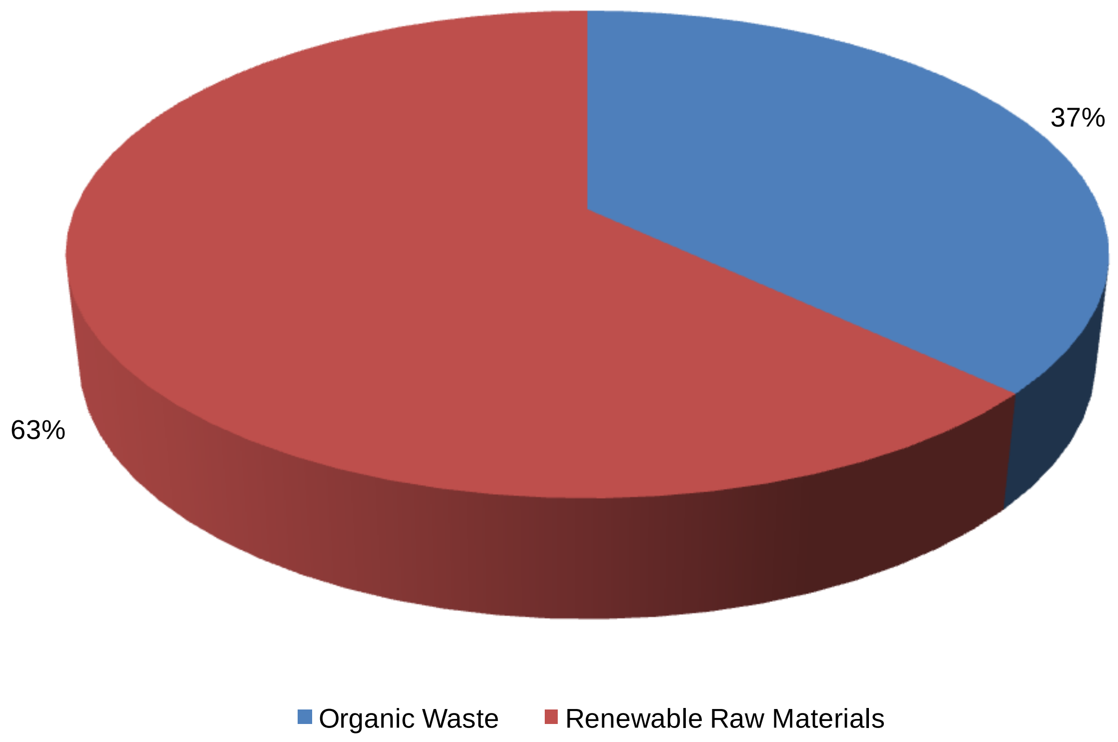


Figure 3.2: Feedstock/substrates used in Germany (Fachagentur Nachwachsende Rohstoffe e.V. 2009c)

Manufacturers

There are large numbers of biogas plant manufacturers in Bavaria. Thus, biogas plants from different manufacturers are chosen, some biogas plants are also do-it-yourself biogas plants (Göbel and Zörner 2006). Taking this fact into account, the ten investigated biogas plants consist of four do-it-yourself plants and six plants from various manufacturers.

Type of Digester

Biogas plants in Bavaria typically consist of two heated tanks and one non-covered residue storage tank (Röhling and Wild 2008). According to an analysis by Ehrmann and Köhnlein (2008), the most common digester types are vertical digesters (93 %) The selection of the ten biogas plants is based on these conditions.

In summary, the ten selected biogas plants represent the structure of biogas plants within Bavaria (Table 3.1). Biogas plant operators can make use of the analysis and approaches of this thesis to compare their own plants with others.

Table 3.1: Selected biogas plants

<table>
<tr><th></th><th>kW_{el}</th><th>CHP-Unit</th><th>Feedstock</th><th>Manufacturer</th><th>Type of Digester</th><th>Start of Operation</th></tr>
<tr><td>BY1</td><td>30</td><td>Pilot Injection</td><td rowspan="7">RRM + Slurry</td><td>do-it-yourself</td><td>vertical</td><td>1999</td></tr>
<tr><td>BY2</td><td>100</td><td>Gas</td><td>do-it-yourself</td><td>vertical</td><td>2002</td></tr>
<tr><td>BY3</td><td>175</td><td>Gas</td><td>UTS Biogastechnik GmbH/ do-it-yourself</td><td>vertical</td><td>2004</td></tr>
<tr><td>BY4</td><td>250</td><td>Gas</td><td>UTS Biogastechnik GmbH</td><td>vertical</td><td>2005</td></tr>
<tr><td>BY5</td><td>190</td><td>Gas</td><td>UTS Biogastechnik GmbH</td><td>vertical</td><td>2005</td></tr>
<tr><td>BY6</td><td>320</td><td>Pilot Injection</td><td>Schmack Biogas AG</td><td>horizontal/ vertical</td><td>2001</td></tr>
<tr><td>BY7</td><td>380</td><td>Gas</td><td>Engineering Office Dyckhoff/do-it-yourself</td><td>vertical</td><td>2005</td></tr>
<tr><td>BY8</td><td>380</td><td>Gas</td><td>RRM</td><td>NQ Anlagentechnik GmbH</td><td>vertical</td><td>2006</td></tr>
<tr><td>BY9</td><td>526</td><td>Gas</td><td rowspan="2">RRM + Slurry</td><td>Cowatec AG</td><td>horizontal /vertical</td><td>2006</td></tr>
<tr><td>BY10</td><td>560</td><td>Gas</td><td>Biogas Hochreiter GmbH</td><td>vertical</td><td>2002</td></tr>
</table>

3.2 Data Acquisition

The acquisition of data from the 10 biogas plants is a central task within the project. Thus, all available information of the plants is recorded systematically. From both the on-site inspection of the plants and the communication with the biogas plant operators, information regarding the fundamental structure, the substrate mixture and the operational mode of the plants is collected. The additional examination includes photographic documentation and an analysis of operational logs. Furthermore, temporary on-site measurements are carried out regarding

- parasitic electric energy,
- biology,
- methane emissions,
- composition of biogas.

3.2.1 Measurements

The focus within the project is on the recording of data with regard to the composition of biogas, parasitic electric energy and methane emissions. Therefore, three measurements are selected.

3.2.1.1 Leakage Detector

For the identification of methane emissions, a leakage detector (Dräger MSI Sensit HXG) is used (Figure 3.3). This device is equipped with a semi-conductor sensor which has a sensitivity of 10 ppm methane. To identify methane leaks, the focus is on all components which are responsible for the conduction of biogas or are directly connected to active substrate.

Figure 3.3: Leakage detector (Dräger MSI Sensit HXG 2009)

3.2.1.2 Gas Analyser

The COMBIMASS GA-M of the manufacturer Binder Engineering is a portable infrared gas analyser which compensates temperature and pressure (Figure 3.4). It is designed to analyse the composition of biogas.

Figure 3.4: COMBIMASS GA-M (Binder Combimass GA-M 2009)

This means, the concentration of methane (CH_4), carbon dioxide (CO_2), oxygen (O_2), hydrogen sulphide (H_2S) and ammonia (NH_3) can be measured. The measurement range of the individual sensors is shown in Table 3.2. Knowing the composition of biogas allows conclusions to be drawn about the biogas production process.

Table 3.2: Measurement range and accuracy of COMBIMASS GA-M (Binder GmbH 2007)

Sensor	Measurement range	Typical accuracy	Measurement technique
CH_4	0 - 100 %	0.2 % at 5 % 1.0 % at 50 % 2.0 % at 100 %	Infrared; wear-free
CO_2	0 – 100 %	0.1 % at 10 % 1.0 % at 50 % 2 % at 100 %	Infrared; wear-free
O_2	0 – 25 %	0.5 %	Electrochemical
H_2S	0 – 2,000 ppm	3 % at 100 % of measuring range 1 % at 10 % of measuring range	Electrochemical
NH_3	0 – 1,000 ppm	3 % at 100 % of measuring range 1 % at 10 % of measuring range	Electrochemical

3.2.1.3 Power Quality Analyser

The Fluke 435-Power Quality Analyser is used to measure the power consumption (Figure 3.5). This device has numerous features such as measuring the present power and energy consumption of individual consumers as well as overall systems (biogas production process, CHP-Unit). There is also the possibility of long-term measurement recording. Thus, the power consumption of components such as agitators or feeding systems can be observed.

Figure 3.5: Fluke 435-Power Quality Analyser (Fluke 435-Power Quality Analyser 2009)

Table 3.3: Fluke 345-Power Quality Analyser accuracy

Component of power measurement	**Measurement range**	**Accuracy**
Voltage	48 V – 600 V	0.1 % of V_{nom}
	600 V – 1,000 V	0.1 V of reading
Ampere (excluding probe accuracy which can be found in Appendix C)	0 A – 200 A	± (0.5 % of reading + 5 counts)
	200 A – 3000 A	± (0.5 % of reading + 20 counts)

3.2.2 Biochemical Analysis

Additional information about the operational mode of the selected biogas plants is gathered by biochemical analyses. Samples are taken from the digester, the post-digester and the used substrates and analysed according to the parameters shown in (Table 3.4).

Furthermore, the remaining biogas potential in the residue storage tanks is analysed by taking samples from the connection between the post-digester and residue storage tank.

Thus, the avoided (covered residue storage tank) or emitted (non-covered residue storage tank) amount of methane can be determined.

3.3 Data Evaluation

Data gathered from on-site inspections, the operational logs and the systematic recording of further information is used to define comparable process variables, to create plant schemes and to describe the operational mode of the plants.

Based on the measurements, additional specific values are created and an evaluation of methane leaks and of the parasitic electric energy is carried out.

3.3.1 Figures for Biogas Production

To compare the biogas plants with each other, performance figures are defined. The most important figures are described in the Chapters 3.3.1.1 - 3.3.1.3.

Table 3.4: Parameters of the biochemical analysis

Type	Description	Unit	Analysis technique
pH-Value		-	EN 12176:1998
EC	Electric conductivity	mS/cm	EN 27888:1993
VOA	Volatile organic acid	g HAc_{eq}/l	Potentiometric tritration according to Nordmann
TIC	Total inorganic carbon	g HAc_{eq}/l	Potentiometric tritration according to Nordmann
VOA/TIC	VOA-TIC-ratio	-	
NH_4^+-N	Ammonia nitrogen	g/l	Tube test LCK 303 (Hach Lange)
DM	Dry Matter	g/kg	EN 12880:2000
oDM	Organic Dry Matter	g/kg	EN 12879:2000
AcOH	Acetic acid	g/l	Gas-chromatographic
PPA	Propionic acid	g/l	Gas-chromatographic
BTA	Butyric acid	g/l	Gas-chromatographic
iBTA	Iso butyric acid	g/l	Gas-chromatographic
PTA	Valeric acid	g/l	Gas-chromatographic
iPTA	Iso Valeric acid	g/l	Gas-chromatographic
CA	Caproic acid	g/l	Gas-chromatographic
HAc-Eq	Acetic acid equivalent	g HAc_{eq}/l	Calculated from the digestion acids (AcOH – CA)

3.3.1.1 Figures for Substrate Supply

In order to determine the hydraulic retention time and the volume load, the daily added feedstock volume, the dry matter and the organic dry matter of the substrate need to be known.

To achieve this, it is necessary to measure the volume of the added feedstock. Depending on the availability of measurement equipment at the plants, the amount of daily added feedstock is recorded. If no measurement equipment is installed, the determination of the added feedstock is realised in one of two alternative ways.

One way of determination is to calculate the added feedstock by taking the volume of the fore-loader shovel and the number of drives per day into consideration. The other way is to measure or estimate the density of each substrate and calculate the daily added feedstock mass. Due to fluctuating loading levels of the shovel, the calculated daily added feedstock volume is just an estimated value.

Dry matter (DM) is the water free content of a substrate sample when completely dried at a temperature of 105 °C. The dry matter contains organic as well as inorganic components (Fachagentur Nachwachsende Rohstoffe e.V. 2009a).

Organic dry matter (oDM) describes the content of organic components in a substrate sample. Only these components are digested and converted into biogas. The proportion of organic components is identified by incineration of the substrate sample. In this process, a sample is heated for several hours in a muffle furnace at a temperature of 550 °C. At the end, ashes remain. The difference in mass between the dried substrate sample and its ash is the proportion of oDM. This reference value is used to describe the volume load and the biogas yield of the biogas production process (Fachagentur Nachwachsende Rohstoffe e.V. 2009a).

A single sample from each substrate is taken. As this is not entirely representative, approved reference values (Döhler et al. 2009a) for the DM- and oDM-content of the digester and post-digester are used. This also ensures comparability.

3.3.1.2 Figures for Operational Mode

The hydraulic retention time (HRT) indicates the mean digestion time of the added feedstock into the digesters. The longer the feedstock remains in the digesters, the higher the gas yield. Common values of the hydraulic retention time vary between 25 and 150 days.

A hydraulic retention time of less than 25 days leads to an inefficient degradation of feedstock. This causes problems within the biochemical process and an insufficient substrate conversion efficiency. Periods of longer than 150 days are more beneficial regarding to the conversion of substrate, however, to achieve this, large investments are necessary to build high volume digesters.

The hydraulic retention time (HRT) is calculated by dividing the active digester volume, i.e. of all tanks which are connected to the CHP-Unit, by the daily added substrate volume (Döhler et. al. 2009a):

$$HRT = \frac{V_{active\ digester}}{\dot{V}_d} \qquad 3.1$$

with

HRT	hydraulic retention time	[d]
$V_{active\ digester}$	active digester volume	$[m^3_{active\ digester}]$
$\dot{V}_d$	daily added substrate volume	$\left[\frac{m^3}{d}\right]$

The volume load indicates the amount of organic dry matter added to the digester per m³ active digester and per time. It is a figure for the load of the biochemical process inside the digester. The hydraulic retention time and the volume load are inversely proportional. A high volume load means a high amount of added substrate, hence, a low hydraulic retention time.

The volume load B_R is calculated by dividing the daily added organic dry matter by the active digester volume (Fachagentur Nachwachsende Rohstoffe e.V. 2009a):

$$B_R = \frac{\dot{m}_{oDM,\ d}}{V_{active\ digester}} \qquad 3.2$$

with

B_R	volume load	$\left[\frac{kg_{\ oDM}}{m^3_{\ active\ digester}\ x\ d}\right]$

$\dot{m}_{oDM,\,d}$ daily added oDM $\left[\frac{kg_{oDM}}{d}\right]$

$V_{active\ digester}$ active digester volume $[m^3_{active\ digester}]$

The specific digester volume indicates the active digester volume $V_{active\ digester}$ per electric capacity of the CHP-Unit(s) for each biogas plant:

$$\text{specific digester volume} = \frac{V_{active\ digester}}{P_{B,\ CHP}} \qquad 3.3$$

with

specific digester volume $\left[\frac{m^3_{active\ digester}}{kW_{el}}\right]$

$V_{active\ digester}$ active digester volume $[m^3_{active\ digester}]$

$P_{B,\ CHP}$ electric capacity of CHP-Unit(s) $[kW_{el}]$

3.3.1.3 Figures for Biogas Production

For the determination of the methane yield, the daily amount of methane produced has to be measured. Due to inaccuracy in measuring the volume flow of biogas, a simplification is used: The produced amount of biogas is assumed to be equal to the consumed amount of biogas by the CHP-Units. This means variations in the fill levels of the gas-holders are not considered. The manufacturers` information regarding the electric efficiency of the CHP-Unit is used to calculate the needed energy of methane $E_{methane,\ d}$ by means of the daily gross electricity production $E_{el,\ gross,\ d}$. Knowing the calorific value of methane $H_{L,\ methane,\ norm}$ (9.97 kWh/m³) (Fachagentur Nachwachsende Rohstoffe e.V. 2009b), the daily methane volume flow $\dot{V}_{methane,\ d}$ and the methane yield can be calculated:

$$E_{methane,\ d} = \frac{E_{el,\ gross,\ d}}{\eta_{electric,\ manufacturer,\ CHP}} \qquad 3.4$$

with

$E_{methane,\ d}$	daily needed energy of methane	$\left[\frac{kWh}{d}\right]$
$E_{el,\ gross,\ d}$	daily gross electric energy production	$\left[\frac{kWh_{el}}{d}\right]$
$\eta_{el,\ manufacturer,\ CHP}$	electric efficiency of CHP-Unit according to manufacturers` information	[%]

$$\dot{V}_{methane,\ d} = \frac{E_{methane,\ d}}{H_{L,\ methane,\ norm}} \qquad 3.5$$

with

$\dot{V}_{methane,\ d}$	daily methane volume flow	$\left[\frac{Nm^3}{d}\right]$
$E_{methane,\ d}$	daily needed energy of methane	$\left[\frac{kWh}{d}\right]$
$H_{L,\ methane,\ norm}$	9.97	$\left[\frac{kWh}{Nm^3}\right]$

The methane yield is the amount of methane, that is produced from the daily added feedstock. This figure is calculated by dividing the daily needed methane volume flow by the daily added feedstock (Fachagentur Nachwachsende Rohstoffe e.V. 2005):

$$\text{methane yield} = \frac{\dot{V}_{\text{methane, d}}}{\dot{m}_{\text{FM, d}}} \qquad 3.6$$

with

methane yield		$\left[\frac{Nm^3}{t_{FM}}\right]$
$\dot{V}_{\text{methane, d}}$	daily methane volume flow	$\left[\frac{Nm^3}{d}\right]$
$\dot{m}_{\text{FM, d}}$	daily added feedstock	$\left[\frac{t_{FM}}{d}\right]$

For the calculation of the methane productivity, the active digester volume is used for comparison:

$$\text{methane productivity} = \frac{\dot{V}_{\text{methane, d}}}{V_{\text{active digester}}} \qquad 3.7$$

with

methane productivity		$\left[\frac{Nm^3}{m^3_{\text{active digester}} \text{ x d}}\right]$
$\dot{V}_{\text{methane, d}}$	daily methane volume flow	$\left[\frac{Nm^3}{d}\right]$
$V_{\text{active digester}}$	active digester volume	$[m^3_{\text{active digester}}]$

The substrate conversion efficiency is a factor to compare the yield of the added feedstock with values from literature. Standard values for the gas yield are taken from Döhler et al. (2007), Döhler et al. (2009a) and Bayerische Landesanstalt für Landwirtschaft (2010). The theoretical energy production is calculated by considering the specific efficiencies of the CHP-Unit(s). With the aid of the annual amount of added feedstock, the expected annual gross electric energy production is determined:

$$\text{substrate conversion efficiency} = \frac{E_{\text{el, gross, a}}}{E_{\text{el, gross, literature, a}}} \text{ x100} \qquad 3.8$$

with

substrate conversion efficiency		[%]
$E_{\text{el, gross, a}}$	annual gross electric energy production	$\left[\frac{kWh_{el}}{a}\right]$
$E_{\text{el, gross, literature, a}}$	annual gross electric energy production, theoretical	$\left[\frac{kWh_{el}}{a}\right]$

A high substrate conversion efficiency shows a good usage of the added feedstock. In the case of pilot-injection CHP-Units, the amount of ignition oil (calorific value: 10 kWh/l) is taken into consideration when calculating the electricity production.

3.3.2 Figures for Biogas Utilisation

A number of figures are defined for the comparison of the biogas utilisation.

For this reason, the maximum theoretical usage rate of the CHP-Units is used to compare the biogas plants with each other, instead of using the operating hour counters of the CHP-Unit(s). The theoretical usage rate indicates how many hours per year, at maximum power output, would have been necessary to generate the gross electricity output. This figure is not the actual amount of operating hours of the CHP-Unit(s), but it indicates the utilisation of the electric capacity of the CHP-Unit(s) (Dachs and Rehm 2006).

$$\text{theoretical usage rate}= \frac{E_{el,\ gross,\ a}}{P_{B,\ CHP} \times 8.760h} x100 \qquad 3.9$$

with

theoretical usage rate		[%]
$E_{el,\ gross,\ a}$	annual gross electric energy production	$\left[\frac{kWh_{el}}{a}\right]$
$P_{B,\ CHP}$	electric capacity of CHP-Unit(s)	$[kW_{el}]$

A high theoretical usage rate of the CHP-Unit(s) can be a result of several conditions such as a properly dimensioned biogas plant, an operation of processes free of failure and a minimum amount of down time caused by maintenance and repair work.

The theoretical usage rate can also be outlined with the theoretical full load hours of the CHP-Unit(s):

$$\text{theoretical full load hours}= \frac{E_{el,\ gross,\ a}}{P_{B,\ CHP}} \qquad 3.10$$

with

theoretical full load hours $\left[\frac{h}{a}\right]$

$E_{el,\ gross,\ a}$ annual gross electric energy production $\left[\frac{kWh_{el}}{a}\right]$

$P_{B,\ CHP}$ electric capacity of CHP-Unit $[kW_{el}]$

The electricity production per tonne fresh mass (FM) indicates the daily gross electric energy that is produced from the daily added feedstock. It is calculated by dividing the daily gross electric energy production by the daily added feedstock (fresh mass):

$$\text{electricity production per } t_{FM} = \frac{E_{el,\ gross,\ d}}{\dot{m}_{FM,\ d}} \qquad 3.11$$

with

electricity production per t_{FM} $\left[\frac{kWh_{el}}{t_{FM}}\right]$

$E_{el,\ gross,\ d}$ daily gross electric energy production $\left[\frac{kWh_{el}}{d}\right]$

$\dot{m}_{FM,\ d}$ daily added feedstock $\left[\frac{t_{FM}}{d}\right]$

The theoretical overall efficiency of a CHP-Unit(s) is a combination of the electric and thermal efficiency. Both can be determined from the ratio between output and input.

The produced energy is the sum of the electric and thermal capacity. The consumed amount of methane and, thus, its energy content, is equal to the thermal input for the CHP-Unit(s). This information is taken from the CHP-Unit manufacturers` data sheets.

To measure the overall efficiency of a CHP-Unit, the input and output have to be recorded. Thus, the measurement of the daily amount of biogas produced is very important. The methane content can be deduced from the precise measurements of the biogas composition. This is very important to evaluate the conversion of biomass to energy. However, obtaining a reliable measurement of the biogas flow rate was not possible because the measurement equipment proved to be inappropriate. Hence, the electric and thermal efficiency of each CHP-Unit is taken from the manufacturers` information instead. The thermal efficiency in the manufacturers` information is the ratio between usable heat flow and thermal input (VDI 4608 2005). The electric efficiency in the manufacturers` information is the ratio between electric capacity of the CHP-Unit and the thermal input (VDI 4608 2005).

Therefore, the produced heat of biogas plants is evaluated the following way:

$$E_{th,\ overall,\ a} = \frac{E_{el,\ gross,\ a}}{\eta_{el,\ manufacturer,\ CHP}} \times \eta_{th,\ manufacturer,\ CHP} \qquad 3.12$$

with

$E_{th,\ overall,\ a}$	annual thermal energy production	$\left[\frac{kWh_{th}}{a}\right]$
$E_{el,\ gross,\ a}$	annual gross electric energy production	$\left[\frac{kWh_{el}}{d}\right]$
$\eta_{th,\ manufacturer,\ CHP}$	thermal efficiency of CHP-Unit according to manufacturers` information	[%]
$\eta_{el,\ manufacturer,\ CHP}$	electric efficiency of CHP-Unit according to manufacturers` information	[%]

As the thermal energy demand for the microbiological process is not measured in most biogas plants, a value of 12.5 % of the produced heat is assumed.

The overall efficiency is then evaluated the following way (Figure 3.6):

$$\text{overall efficiency} = \eta_{el,\ manufacturer,\ CHP} + \eta_{th,\ manufacturer,\ CHP} \cdot \frac{E_{th,\ utilised,\ a} + E_{th,\ process,\ a}}{E_{th,\ overall,\ a}} \qquad 3.13$$

with:

overall efficiency		[%]
$\eta_{el,\ manufacturer,\ CHP}$	electric efficiency of CHP-Unit according to manufacturers` information	[%]
$\eta_{th,\ manufacturer,\ CHP}$	thermal efficiency of CHP-Unit according to manufacturers` information	[%]
$E_{th,\ process,\ a}$	annual thermal energy for heating the microbiological process	$\left[\frac{kWh_{th}}{a}\right]$
$E_{th,\ utilised,\ a}$	annual utilised thermal energy	$\left[\frac{kWh_{th}}{a}\right]$
$E_{th,\ overall,\ a}$	annual thermal energy production	$\left[\frac{kWh_{th}}{a}\right]$

Due to this simplification, the calculated values are considered to be an estimation. However, this procedure ensures comparability among the selected biogas plants.

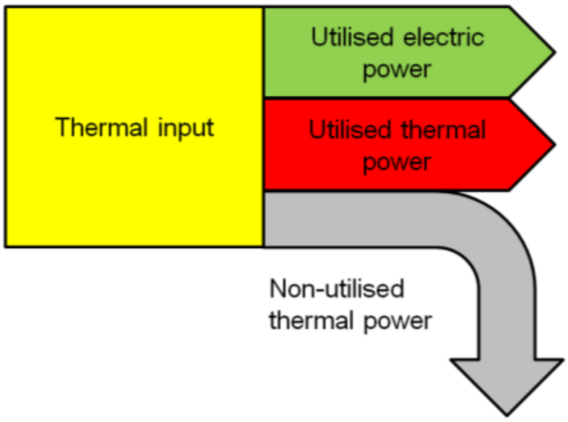


Figure 3.6: Thermal input and overall efficiency

3.3.3 Analysis of Parasitic Electric Energy

The determination of the parasitic electric energy requires a detailed analysis of all electric consumers of the biogas plant.

If electricity meters are available on-site, their data is used to evaluate the electricity consumption, the electricity production and the parasitic electric energy (Dachs and Rehm 2006):

$$\text{parasitic electric energy}=\frac{E_{el,\ consumption,\ d}}{E_{el,\ gross,\ d}}\ x100 \qquad 3.14$$

with

parasitic electric energy		[%]
$E_{el,\ consumption,\ d}$	daily electric energy consumption	$\left[\frac{kWh_{el}}{d}\right]$
$E_{el,\ gross,\ d}$	daily gross electric energy production	$\left[\frac{kWh_{el}}{d}\right]$

If no electricity meters are available, the parasitic electric energy is determined by measuring and multiplying the effective power by the runtime of each component, and adding the individual consumptions:

$$E_{el,\ component\ 1,\ d}=P_{el,\ component\ 1}\ x\ t_{component\ 1,\ d}$$

$$\underline{+E_{el,\ component\ 2,\ d}=P_{el,\ component\ 2}\ x\ t_{component\ 2,\ d}}$$

$$\sum E_{el,\ component\ 1,\ d}\ ,\ E_{el,\ component\ 2,\ d}=\text{electricity consumption} \qquad 3.15$$

with

$E_{el,\ component,\ d}$	daily electric energy consumption of a component	$\left[\frac{kWh_{el}}{d}\right]$
$P_{el,\ component}$	effective power of a component	$[kW_{el}]$
$t_{component,\ d}$	daily runtime of a component	$\left[\frac{h}{d}\right]$

The measurement of the parasitic electric energy is carried out for every biogas plant. The collected data can, therefore, be checked for plausibility by comparing it with the available electricity meters. Furthermore, the consumers are separated into the electric consumption of the CHP-Unit on the one hand and the biogas production process on the other hand. Measurements of the effective power are carried out over a longer period of time, so power peaks and noticeable problems can be identified. Eventually, several components are pooled into modules such as stirring devices or the feeding system. With this modular structure values for comparison are evaluated.

The specific stirring electric energy consumption is evaluated in two different ways. Either the stirring electric energy consumption is compared with the active digester volume and the stirring runtime, or it is compared to the daily added feedstock (Dachs and Rehm 2006):

$$E_{spec.\frac{stirring}{t_{FM}}} = \frac{\sum E_{stirrer,\ d}}{\dot{m}_{FM,\ d}} \qquad 3.16$$

with

$E_{spec.\frac{stirring}{t_{FM}}}$	specific stirring electric energy consumption per t added feedstock	$\left[\frac{kWh_{el}}{t_{FM}}\right]$
$\sum E_{stirrer,\ d}$	daily total stirring electric energy consumption	$\left[\frac{kWh_{el}}{d}\right]$
$\dot{m}_{FM,\ d}$	daily added feedstock	$\left[\frac{t_{FM}}{d}\right]$

$$E_{spec.,\ d.\frac{stirring}{active\ digester}} = \frac{\sum E_{stirrer,\ d}}{V_{active\ digester}} \qquad 3.17$$

with

$E_{spec.,\, d.\frac{stirring}{active\ digester}}$	specific stirring electric energy consumption per 100 m^3 active digester volume	$\left[\frac{kWh_{el}}{100m^3_{active\ digester} \times d}\right]$
$\sum E_{stirrer,\, d}$	daily total stirring electric energy consumption	$\left[\frac{kWh_{el}}{d}\right]$
$V_{active\ digester}$	active digester volume	$[m^3_{active\ digester}]$

Feeding systems are compared with each other by dividing each feeding system electric energy consumption by its added feedstock (specific feeding system electric energy consumption) (Dachs and Rehm 2006):

$$E_{spec.\frac{feeding\ system}{t_{FM}}} = \frac{E_{feeding\ system,\, d}}{\dot{m}_{FM,\, d}} \qquad 3.18$$

with

$E_{spec.\frac{feeding\ system}{t_{FM}}}$	specific feeding system electric energy consumption per t added feedstock (without slurry)	$\left[\frac{kWh_{el}}{t_{FM}}\right]$
$E_{feeding\ system,\, d}$	daily feeding system electric energy consumption	$\left[\frac{kWh_{el}}{d}\right]$
$\dot{m}_{FM,\, d}$	daily added feedstock (without slurry)	$\left[\frac{t_{FM}}{d}\right]$

3.3.4 Evaluation and Quantification of Methane Emissions

A further important parameter within the investigation of the 10 selected biogas plants is biogas leaks (sources of emissions of methane). These leaks are identified using a leakage detector designed to detect methane. To identify methane leaks, the focus is on all components responsible for the conduction of biogas or directly connected to active substrate. Emissions of methane which are caused by incomplete combustion within the CHP-Units are not considered. Values from literature are used to carry out climate gas balance sheets (Appendix A).

3.3.4.1 Evaluation of Methane Leaks

After the biogas leaks are identified, a classification (Table 3.5) is carried out according to the tick-rate of the leakage detector. The signal of the leakage detector varies between no signal (if no emissions are detected) and a siren-signal (if very high emissions are detected).

Table 3.5: Classification of methane emissions

Emission		Symbol
Category C	none	- -
	low	-
Category B	medium	0
Category A	high	+
	very high	+ +

Eventually, the identified biogas leaks are summarised and classified according to the tick-rate (Table 3.6).

Table 3.6: Example for the classification of methane emissions

Biogas Leak	Classification
Open Overflow	+
Feeding System	
on	+
off	-
Porthole	
Digester	0
Post-digester	- -
Emergency opening	+ +
Gasholder	+
Non-gastight Residue storage tank	-

3.3.4.2 Categorisation of Methane Leaks

Biogas leaks are divided into 3 categories:

- methane emissions caused by design errors,
- deficiencies due to lack of maintenance / due to ageing,
- mistakes in assembly or installation.

As a result, the causes of biogas leaks (methane leaks) become obvious and the potential to avoid those leaks can be assessed.

3.3.5 Leakage rate

The leakage rate of the identified biogas leaks cannot be determined by the leakage detector. Hence, the leakage rate $\dot{V}_{leakage}$ is calculated according to Bernoulli:

$$\dot{V}_{leakage} = A_{leakage} x \sqrt{\frac{2 \times \Delta p}{\rho_{Biogas}}} \qquad 3.19$$

with

$\dot{V}_{leakage}$	leakage rate of biogas	$\left[\frac{m^3}{s}\right]$
$A_{leakage}$	area of biogas leak	[m²]
Δp	pressure difference between inside digester and atmosphere	[mbar]
ρ_{biogas}	density of biogas	$\left[\frac{kg}{m^3}\right]$

The quantification of methane emissions of open overflows is carried out by considering the gas yield of the substrate volume inside. Methane emissions from pre-storage tanks are calculated with emission factors (organic manure/slurry according to Umweltbundesamt 2002; Appendix A).

3.3.6 Greenhouse Gas Balance Sheet

The basis for the greenhouse gas balance sheets is the acquisition of data regarding parasitic electric energy and methane emissions. This analysis is carried out by the Institut für Energie- und Umweltforschung (IFEU) according to ISO 14040 and ISO 14044. Within the analysis, the cropping, storing and feeding of substrates are considered. Digestion, utilisation of biogas and the storage of digestate are also taken into account.

The objective of this analysis is the determination of factors which have an effect on the greenhouse gas balance of biogas plants. As a result, the potential for reducing greenhouse gas emissions with biogas plants can be assessed.

To ensure comparability, all greenhouse gases are converted into their CO_2-equivalent (Table 3.7).

Table 3.7: Greenhouse gas potential of gases (Intergovernmental Panel on Climate Change 2007)

Greenhouse Gas	CO_2-Equivalent [$kg_{CO2\text{-}Eq.}$/kg]
Carbon Dioxide	1
Methane, Renewable Origin	25
Methane, Fossil Origin	27.75
Nitrous Oxide	298

The greenhouse gas balances of the investigated biogas plants are carried out according to the assumptions and data which can be found in Appendix A.

3.3.7 Profitability

The economic success of biogas plants depends on several parameters. For the comparison of the 10 selected biogas plants, the return on assets (ROA) is evaluated. As the economic situation of the biogas sector has improved since the amendment to the EEG in 2009, the ROA for 2008 and 2009 are evaluated.

To ensure comparability, both plant-related factors and non-plant-related factors are used to evaluate the economic situation.

Plant-related factors are the amount of electricity fed into the public grid, heat utilisation, feedstock, electricity purchase and subsidies (revenue) from the German renewable energies act (2008 and 2009).

Non-plant-related factors are cost for feedstock, working materials, investments and working hours. This information is adopted from the *KTBL-Biogasrechner* (Kuratorium für Technik und Bauwesen in der Landwirtschaft 2010).

3.3.7.1 Revenue

The revenue per year consists of the subsidies from the German renewable energies act. These subsidies consist of a basic compensation, a renewable raw material bonus, a slurry bonus and a cogeneration bonus.

The income from selling heat to external consumers is also considered.

3.3.7.2 Costs

The largest proportion of current expenses is the cost of feedstock. The basis for its calculation is the amount of feedstock used and the specific substrate cost. To ensure comparability, uniform feedstock cost is considered and taken from the *KTBL-Biogasrechner* (Kuratorium für Technik und Bauweisen in der Landwirtschaft 2010). Furthermore, data for working hours and cost of purchased electricity and ignition oil are taken into account.

Additional information regarding the calculation of the ROA is shown in Table 3.8.

Table 3.8: Parameters for the calculation of the ROA (according to Kuratorium für Technik und Bauwesen in der Landwirtschaft; Leibnitz Institut für Agrartechnik Potsdam-Bornim e.V. 2010)

Volume of Investment		I_V	Calculation
Investment	Building	I_G	$I_V \cdot 68\ \%$
	Technical equipment	I_T	$I_V \cdot 32\ \%$
	Debt-financing	f	66 %
	Interest rate	i	6 %
Depreciation	Building	D_B	$I_G \cdot 6.25\ \%$
	Technical equipment	D_T	$I_T \cdot 12.5\ \%$
Financing cost	Building	F_B	$I_G \cdot f \cdot i$
	Technical equipment	F_T	$I_T \cdot f \cdot i$
Maintenance cost	Building	M_B	$I_G \cdot 1\ \%$
	Technical equipment	M_T	$I_T \cdot 4\ \%$
Working materials			$I_V \cdot 2\ \%$
Insurance			$I_V \cdot 2\ \%$
Wage			15 €/h
Electricity cost			0.15 €/kWh$_{el}$
Interest rate working assets			4 %; 6 months

4 Evaluation and Weak Point Analysis

In this chapter the collected data from the 10 selected biogas plants is evaluated. A description of each biogas plant and the time periods and measurements taken on each plant can be found in Appendix B. For the identification of approaches with high potential for both economic and ecological optimisation, data is summarised and compared following the biogas production process.

4.1 Substrate Supply

4.1.1 Distance of Farmland

Figure 4.1 shows the mean and maximum distances of the 10 selected biogas plants.

The maximum distance from farmland to biogas plant varies from 4 km to 10 km. The average of the mean distances is 3.1 km. Furthermore, Figure 4.1 shows that there is no direct correlation between transport distance and electric capacity of the biogas plants, as might be expected. This can be traced back to specific preconditions such as owned farmland or purchased feedstock.

As a result, it can be seen that the distances for the supply of feedstock are not extremely far and, thus, do not have the potential for optimisation in Bavaria.

4.1.2 Required Farmland

The amount of farmland required is an indicator for the evaluation of biogas plant efficiency.

The proportion of required farmland to electric capacity varies from 0.34 ha/kW$_{el}$ to 0.63 ha/kW$_{el}$ (Figure 4.2).

The mean farmland per electric capacity is 0.44 ha/kW$_{el}$. This value corresponds to the required farmland of 0.43 ha/kW$_{el}$ given in literature (Göbel and Zörner 2006).

The low farmland requirement of biogas plants such as BY1 and BY2 can be traced back to their high usage of organic manure. All of the selected biogas plants are on-farm biogas plants, thus, an accurate determination between farmland for the production of biogas and livestock breeding is difficult.

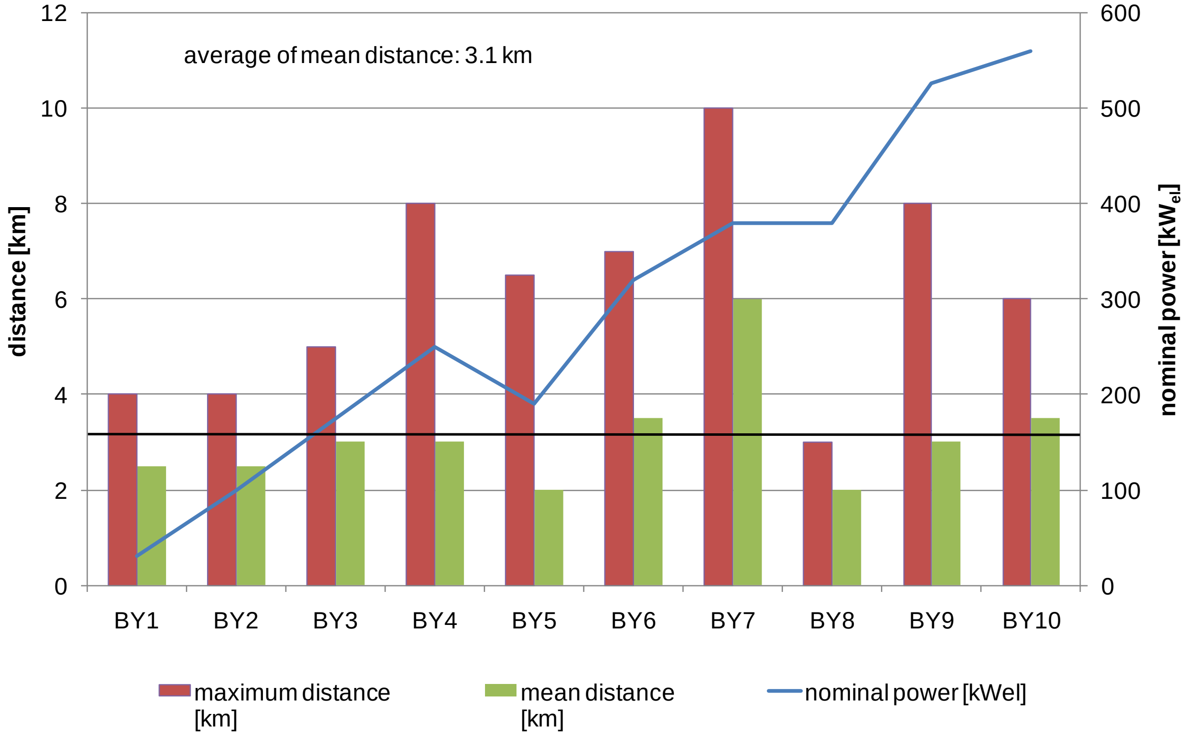


Figure 4.1: Distance from farmland to biogas plant

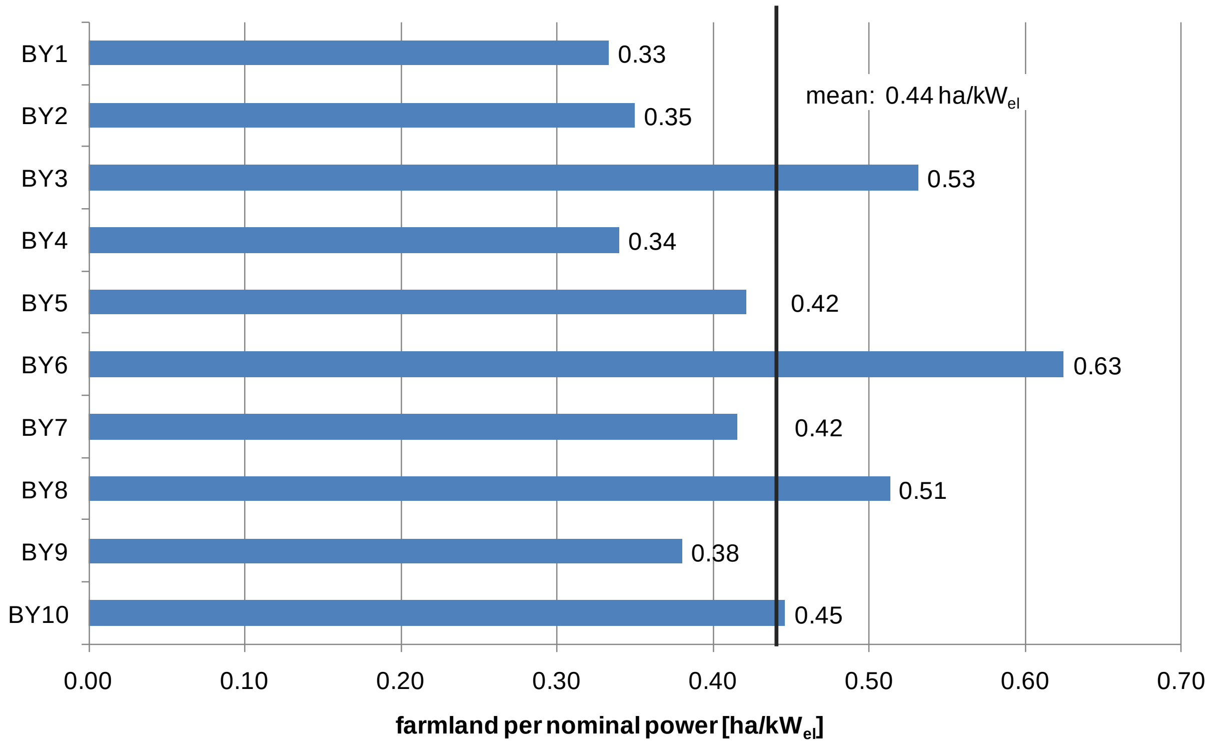


Figure 4.2: Required farmland per electric capacity

4.1.3 Substrate Origin: Owned or Purchased

The origin of substrates is shown in Figure 4.3. Feedstock can be grown on own farmland or be purchased off the market. The mean of purchased substrate is 10.8 %, 4 biogas plants do not buy any feedstock.

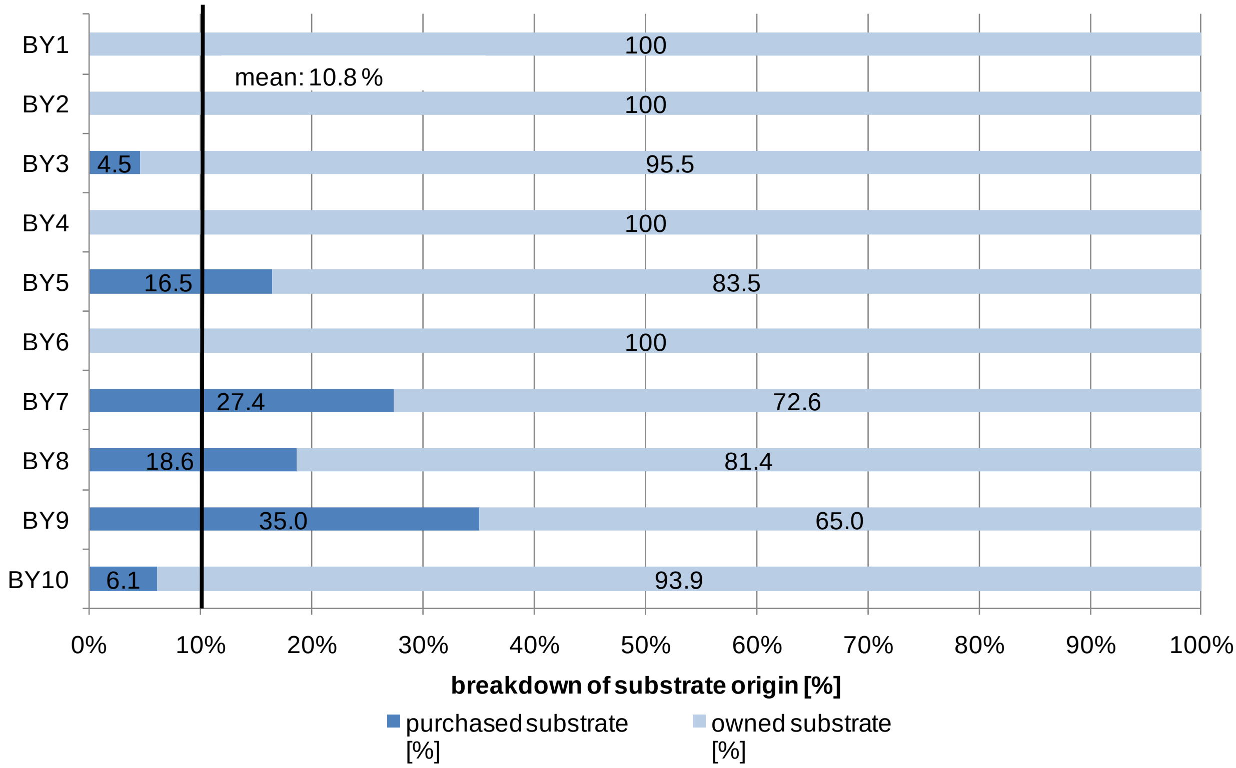


Figure 4.3: Breakdown of substrate origin (owned/purchased)

A low proportion of purchased feedstock is preferable, as the dependency of substrate from the market and rising prices can be avoided. If substrate is purchased, long-term supply contracts are recommended to protect against price fluctuations as seen in the past. However, none of the 10 biogas plants have any supply contracts for substrates, hence, there is an inherent threat to their economic efficiency.

4.2 Loading of Substrate

4.2.1 Silo – Feeding System Distance

The distance from silo to feeding system varies between 60 m and 240 m (Figure 4.4). To load the feeding system, an average distance of 98 m has to be covered.

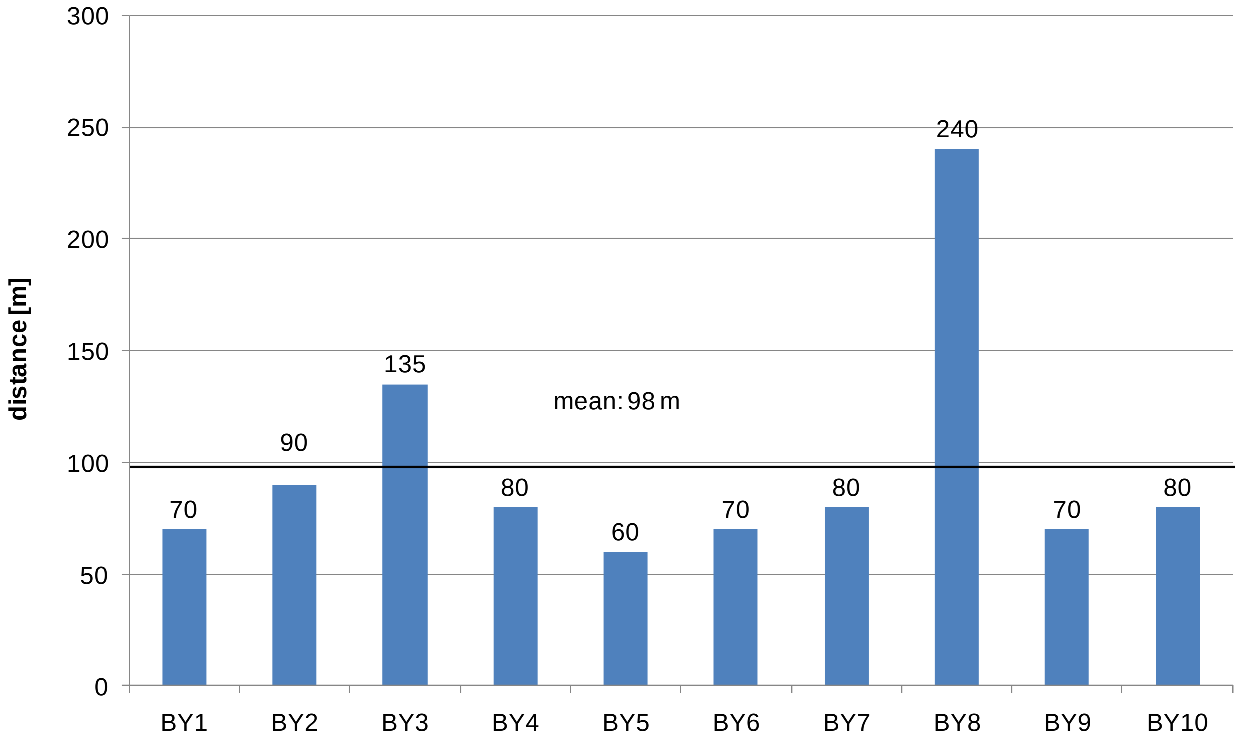


Figure 4.4: Distance from silo to feeding system

The biogas plants BY3 and BY8 exceed the mean distance by far. This can be traced back to the following reasons:

- BY3: Several silos are spread out widely across the farm.
- BY8: While constructing the driveway, bedrock was detected, so the planned driveway had to be changed and thus a longer transport distance.

To reduce fuel consumption and time required, long distances between silo and feeding system need to be avoided.

4.2.2 Feeding System Loading Time

The loading time for the feeding system is determined by the number of trips and the distance between silo and feeding system. Figure 4.5 shows the specific expenditure of time for loading the feeding system in relation to the amount of added feedstock (without slurry).

A detailed analysis of the specific load time expenditure for the feeding system shows major differences. The values vary between 1.4 min/(d·t_{FM}) and 6.2 min/(d·t_{FM}). This wide range can be explained with the different handling systems in use. A further factor is the distance from silo to feeding system.

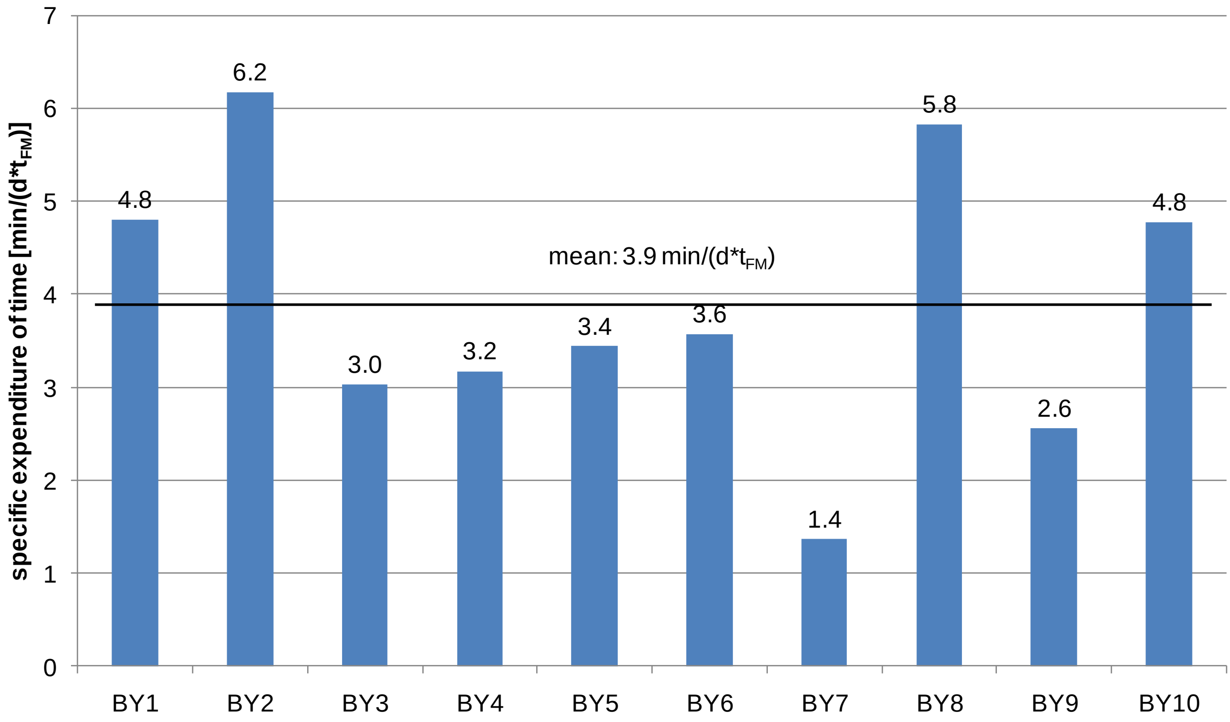


Figure 4.5: Specific load time expenditure for the feeding system

For example, BY7 uses a telescopic handler which can carry 2.5 m³ of feedstock. The mean distance between silo and feeding is only 80 m (Figure 4.6) and the driveway is tarred, enabling a higher speed of the handling system. Due to these conditions, the specific load time expenditure for the feeding system is at the low level of 1.4 min/(d·t_{FM}).

In contrast to this, BY8 has a very high value of 5.8 min/(d·t_{FM}) though it uses the same handling system (telescopic handler) as BY7. Furthermore, the handling system can even carry 3.0 m³ of feedstock. The higher value can, however, be attributed to several reasons. The mean distance from silo to feeding system is very far at 240 m. In addition to this, the driveway is not tarred and there is a difference in altitude (Figure 4.7).

The wide range of values of the specific load time expenditure for the feeding systems within the 10 investigated biogas plants shows a high potential for optimisation.

Figure 4.6: Driveway of BY7 (Bayerisches Landesamt für Vermessung und Geoinformation 2010)

Figure 4.7: Driveway of BY8 (Bayerisches Landesamt für Vermessung und Geoinformation 2010)

4.3 Biogas Production

4.3.1 Fermentation Process

The fermentation process of biogas can be dry or wet, depending on the moisture content of the feedstock. However, all 10 selected biogas plants produce biogas via wet digestion.

A further area for investigation is the type of digester. The orientation of a digester is primarily based on the feedstock used and its consistency. In general, digesters can be classified into 3 types, namely, cylindrical digesters, horizontal digesters and a combination of both types. Cylindrical digesters are used in 8 out of the 10 investigated biogas plants. Two plants use a combination of cylindrical and horizontal digesters (Figure 4.8).

Concrete is used as the construction material for the tanks and the digesters are covered gastight with either foils or concrete ceilings.

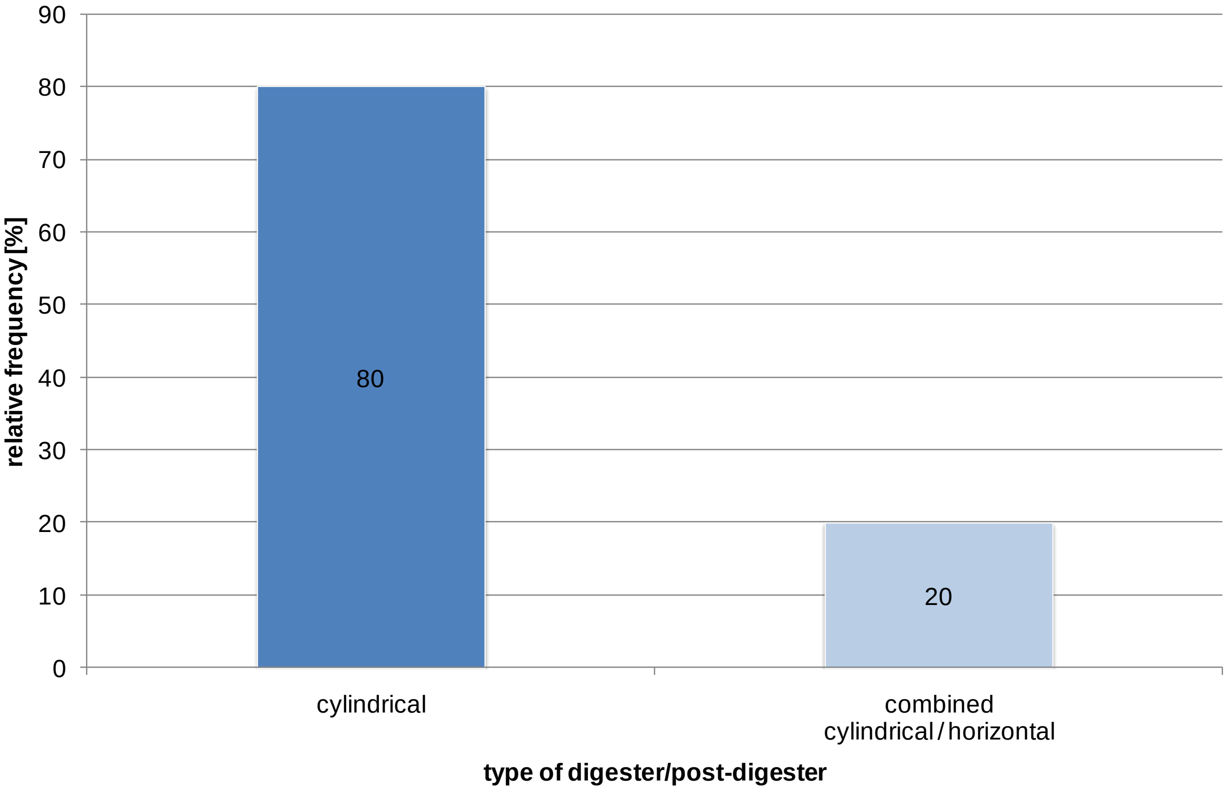


Figure 4.8: Type of digester/post-digester

4.3.1.1 Specific Digester Volume

The specific digester volume of the 10 investigated biogas plants varies between 5.0 m^3/kW_{el} and 13.1 m^3/kW_{el} (Figure 4.9).

In the literature, a range of 4...8 m^3/kW_{el} is suggested (Döhler et al. 2009a). As the mean specific digester volume is higher than the values given in literature, at 9.5 m^3/kW_{el}, a potential for optimisation can be identified.

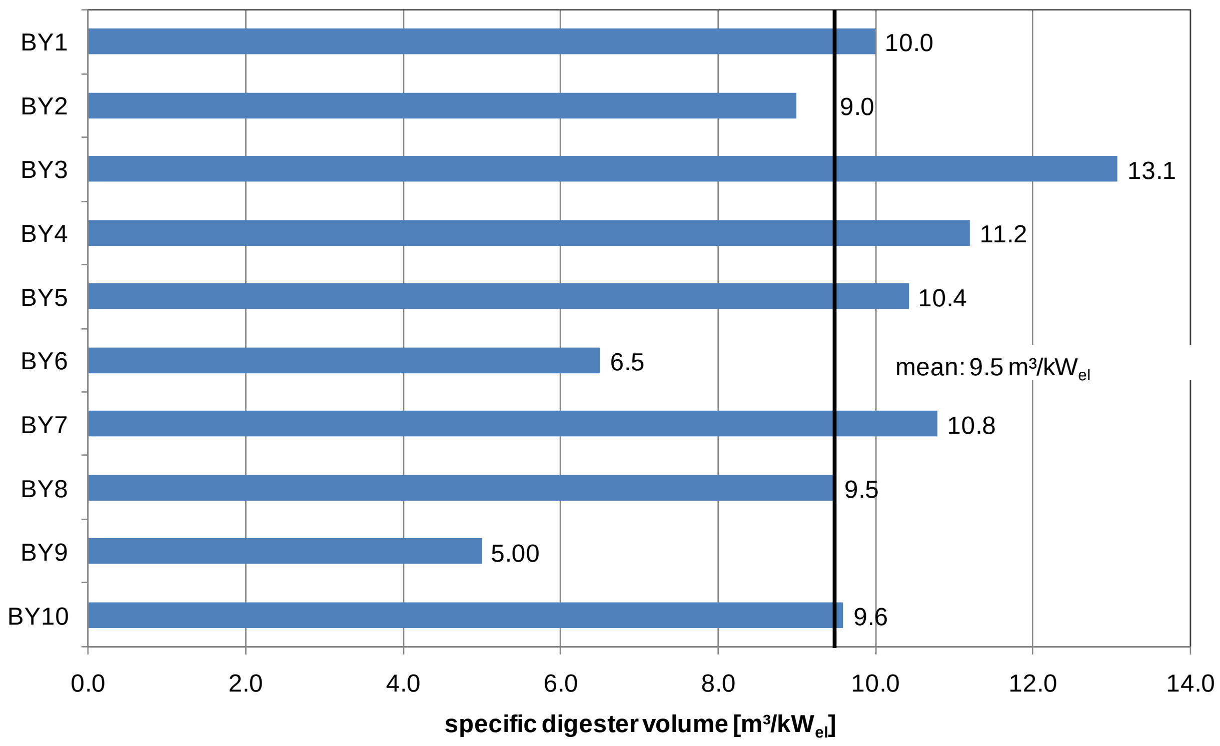


Figure 4.9: Specific digester volume of the investigated biogas plants

4.3.1.2 Volume Load

The mean volume load of the 10 biogas plants is 2.0 $kg_{oDM}/(m^3_{\text{active digester}} \cdot d)$. A comparison to the suggested range of 2...4.7 $kg_{oDM}/(m^3_{\text{active digester}} \cdot d)$ in Döhler et al. (2009a) indicates a considerable portion of unused potential in Bavaria (Figure 4.10).

4.3.1.3 Hydraulic Retention Time

As the hydraulic retention time (HRT) is an indicator for the remaining biogas potential in the residue storage tank and the degradation of feedstock, it is also analysed.

The mean HRT is 84.1 d, it varies from 41 d to 144 d (Figure 4.11). According to literature, the HRT is supposed to be within the range of 35...110 d (Döhler et al. 2009a). A closer look at BY7 shows a HRT of 144 d, which exceeds the suggested 110 d. In contrast to this, BY1 only has a HRT of 41 d.

The influence of the HRT on the remaining biogas potential is analysed in Chapter 4.8.4.

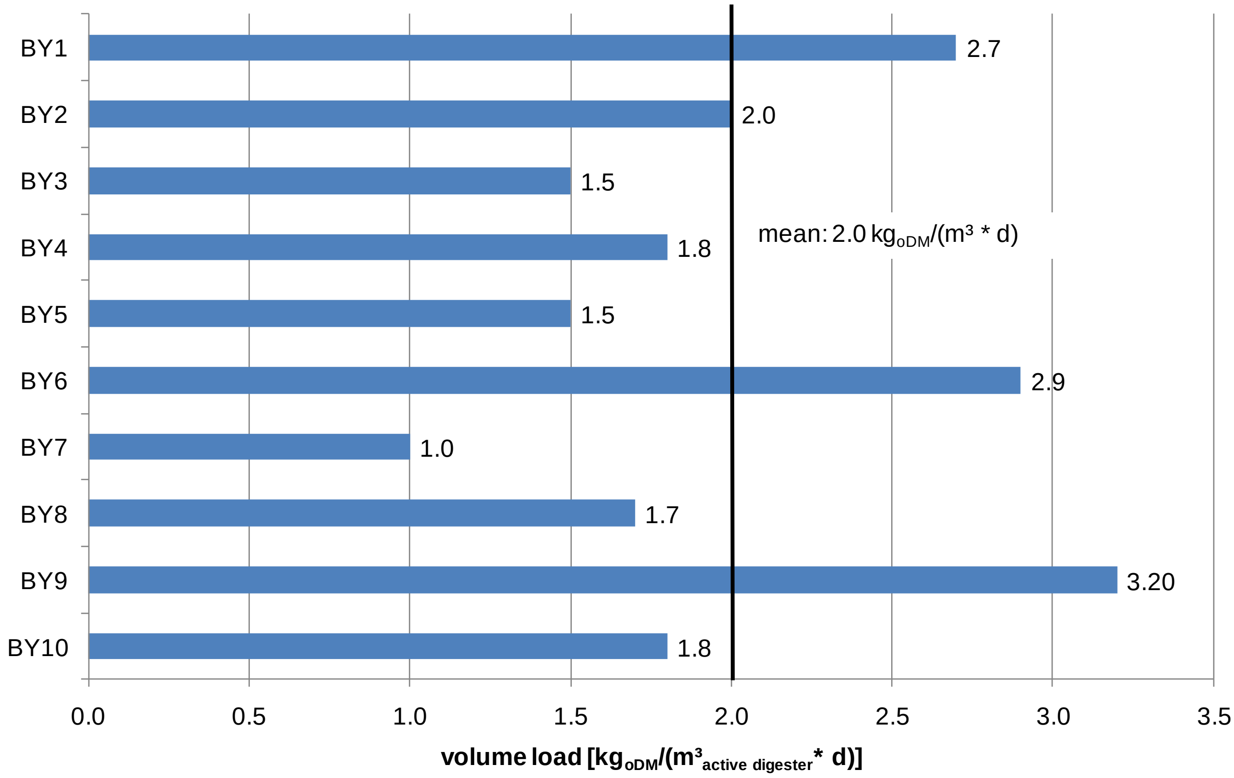


Figure 4.10: Volume load of the investigated biogas plants

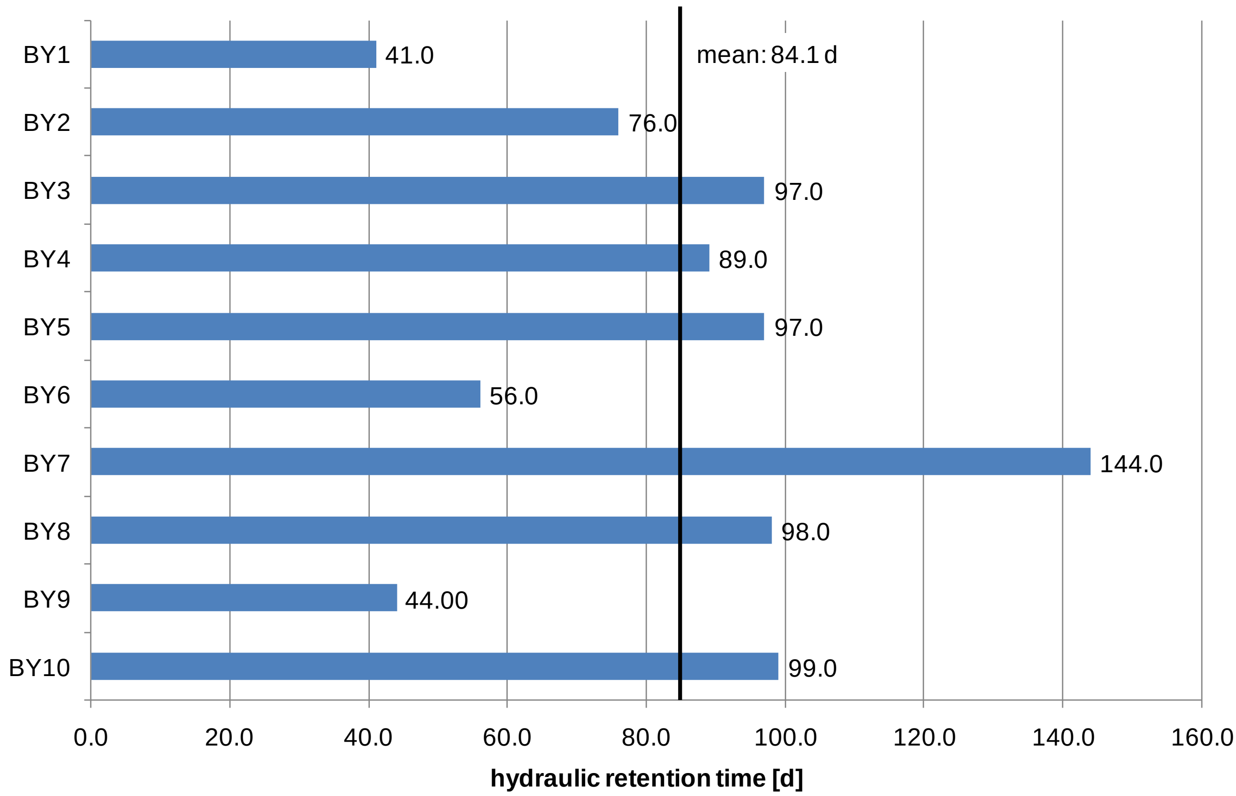


Figure 4.11: Hydraulic retention time of the investigated biogas plants

4.3.1.4 Substrate Conversion Efficiency

The substrate conversion efficiency (SCE) is a factor used to compare the usage of the added feedstock with values from literature. Figure 4.12 shows a wide range of SCE-values from 59 % to 120 % with a mean of 97.7 %. A SCE of less than 90 % (BY1, BY6, BY8) reveals a high potential for optimisation.

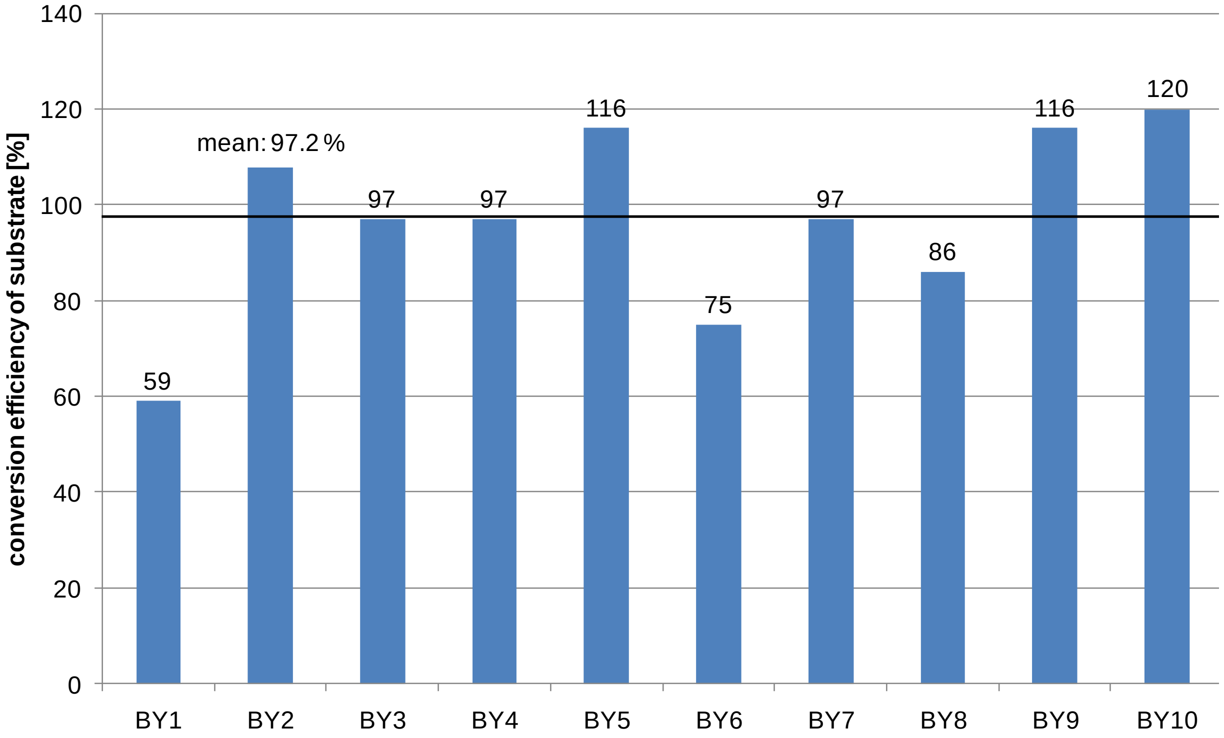


Figure 4.12: Substrate conversion efficiency of the investigated biogas plants

However, the optimisation of the SCE depends on several plant-specific parameters, so the necessary action can hardly be generalised.

4.3.2 Used Substrates

Figure 4.13 shows an analysis of the substrates used. The mean content of slurry from livestock used is 42 %. This indicates that almost all biogas plant operators (except BY8) utilise the bonus for slurry, due to a slurry content of more than 30 %.

A high usage of organic manure also contributes to the reduction of greenhouse gas and a stable microbiological process. However, a high amount of slurry leads to the need for an increased digester volume because of decreased biogas yield.

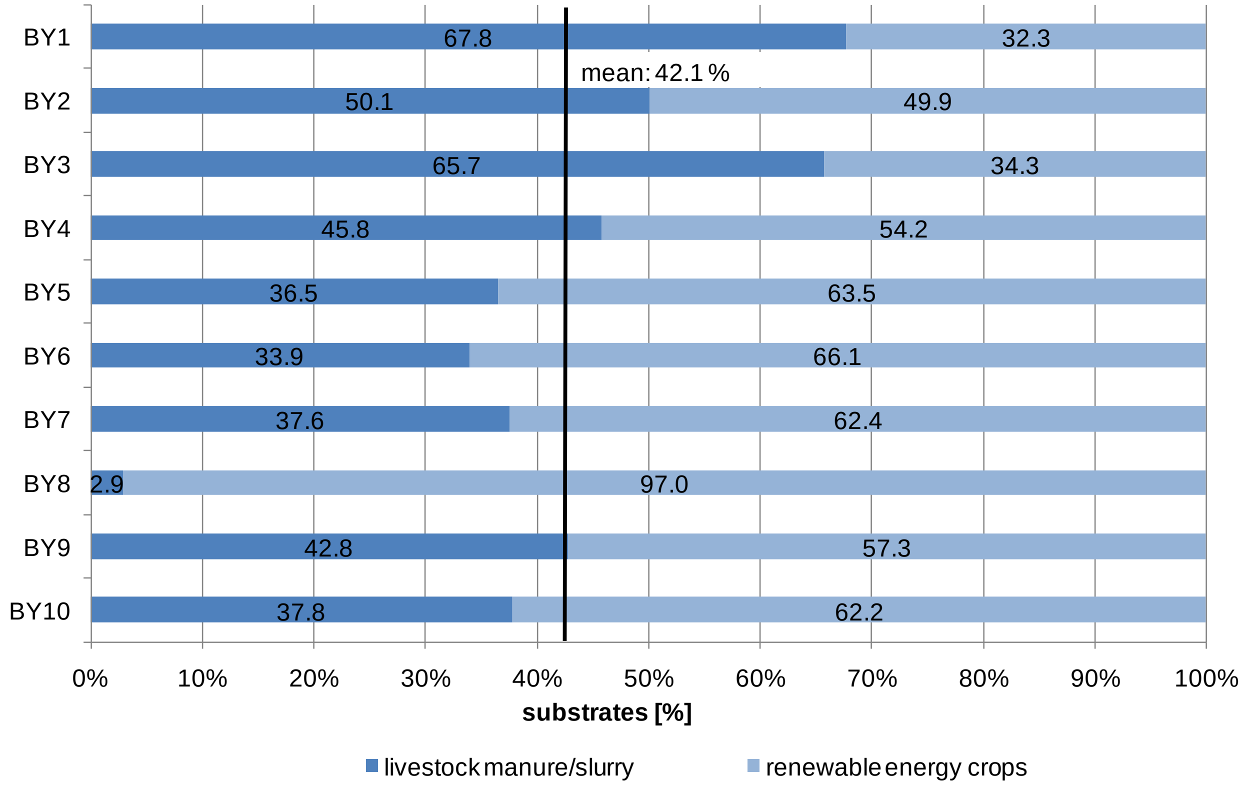


Figure 4.13: Used renewable raw materials of the investigated biogas plants

The most commonly used renewable raw materials are silages such as maize silage (100 %), grass silage (80 %) and whole-crop silage (WCS; 60 %).Cattle and pork slurry are the most frequently used types of organic manure.

4.3.3 Biology

In this section the biochemical process is analysed.

4.3.3.1 Dry Matter (DM)

The dry matter content (DM) of the 10 investigated biogas plants varies from 63.9 g/kg to 89.0 g/kg (Figure 4.14), it is far below the maximum range of 120…150 g/kg which is given in Döhler et al. (2009a).

According to Fachagentur Nachwachsende Rohstoffe e.V. (2009c), the substrate-viscosity rises at a DM-content of more than 100 g/kg. This can affect the stirring ability, but as all biogas plants have a DM-content of less than 100 g/kg, no negative effects are expected.

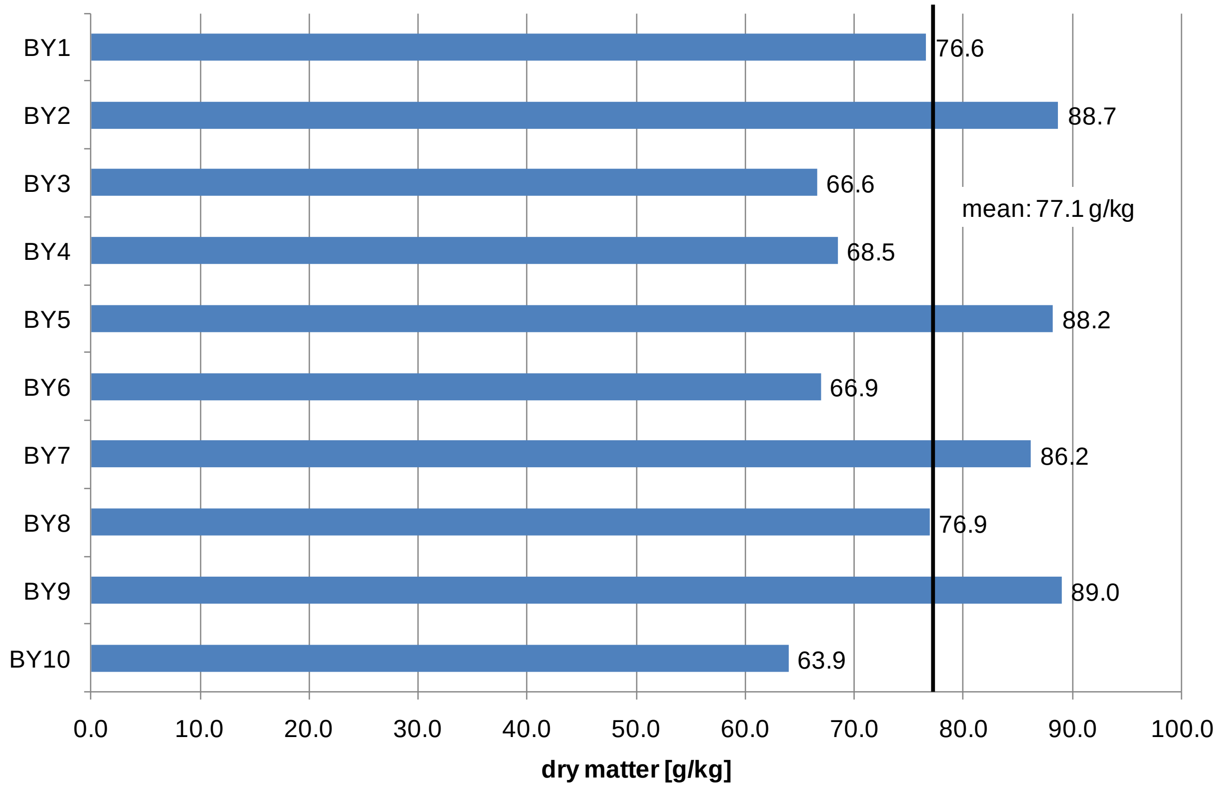


Figure 4.14: Mean dry matter content based on samples from digester/post-digesters

4.3.3.2 pH-Value

The mean pH-Value of the 10 biogas plants in Bavaria is 7.7, varies from 7.4 to 8.0. According to literature, pH-values of 6.8...8.2 are advantageous for the production of methane (Döhler et al. 2009a). Figure 4.15 shows that all pH-Values are within this range.

The production of CO_2 rises when the pH-Value is less than 6.8, followed by an increase in content of hydrogen sulphide and fatty acids, leading to a reduced production of methane (Köttner 2006). At a pH-Value of more than 8.0, the dissociation equilibrium shifts from NH_4 to NH_3, which is toxic for the production of methane (Köttner 2006).

As all biogas plants are within the range of literature, no potential for optimisation is expected.

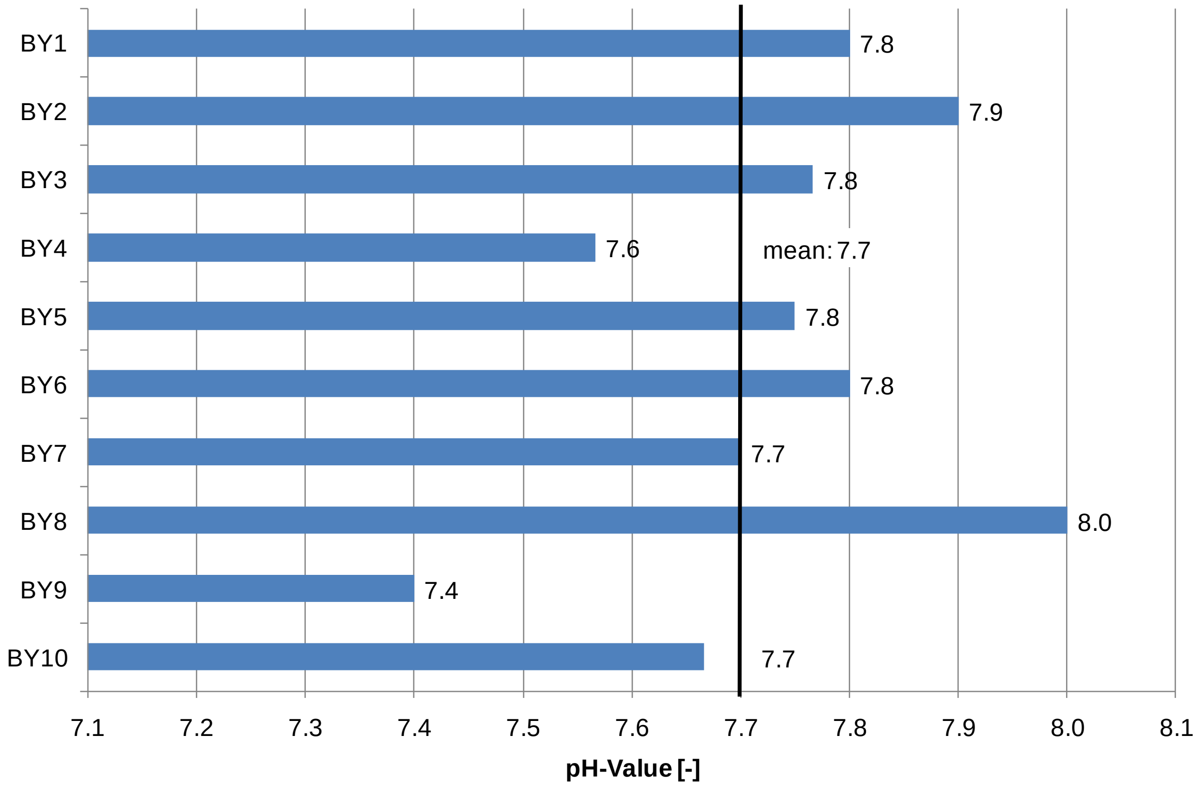


Figure 4.15: pH -Values based on samples from digester/post-digesters

4.3.3.3 VOA/TIC

The ratio of volatile organic acid (VOA) to total inorganic acid (TIC) varies between 0.19 and 0.34 (Figure 4.16). According to Lossie and Pütz (2009), a range of 0.3...0.4 is advantageous for the operation of biogas plants. Values lower than 0.2 indicate that more feedstock should be fed into the digester.

A VOA/TIC-value of more than 0.4 is a sign for over-feeding of the digester (Lossie and Pütz 2009). Malfunctions within the biological process may occur at a value of 0.8 (Effenberger et al. 2007).

Figure 4.16 shows that all investigated biogas plants (except BY7 and BY10) do not use enough feedstock. As a result, the efficiency of these plants can be improved.

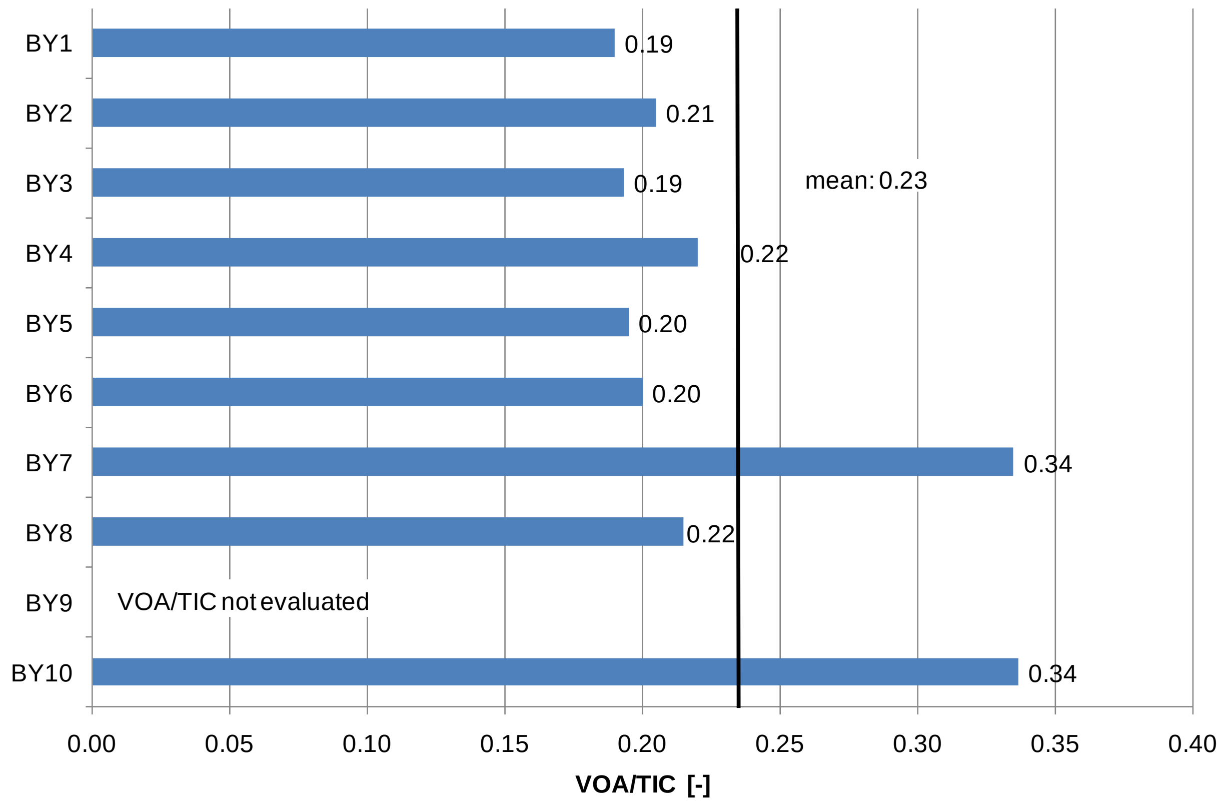


Figure 4.16: Mean of VOA/TIC based on samples from digester/post-digesters

4.3.4 Feeding System

In this section, the type of feeding system for solid feedstock is analysed. All 10 investigated biogas plants use screw-feeding systems.

If the digesters are covered with a concrete ceiling, the feeding systems are located on the concrete ceiling. In other cases, the feeding systems are positioned next to the digesters, the solid feedstock is then conveyed to the top of the tank by several screws.

To compare the different feeding systems, the energetic efficiency is evaluated. Therefore, the specific feeding system electric energy consumption per added solid feedstock is analysed (Figure 4.17).

The fluctuating energy consumption of the 10 biogas plants is notable. Though the mean specific feeding system electric energy consumption is 1.1 kWh_{el}/t_{FM} and, thus, largely within the range in literature of 0.4...0.9 kWh_{el}/t_{FM} (Döhler et al. 2009a), there is potential for optimisation.

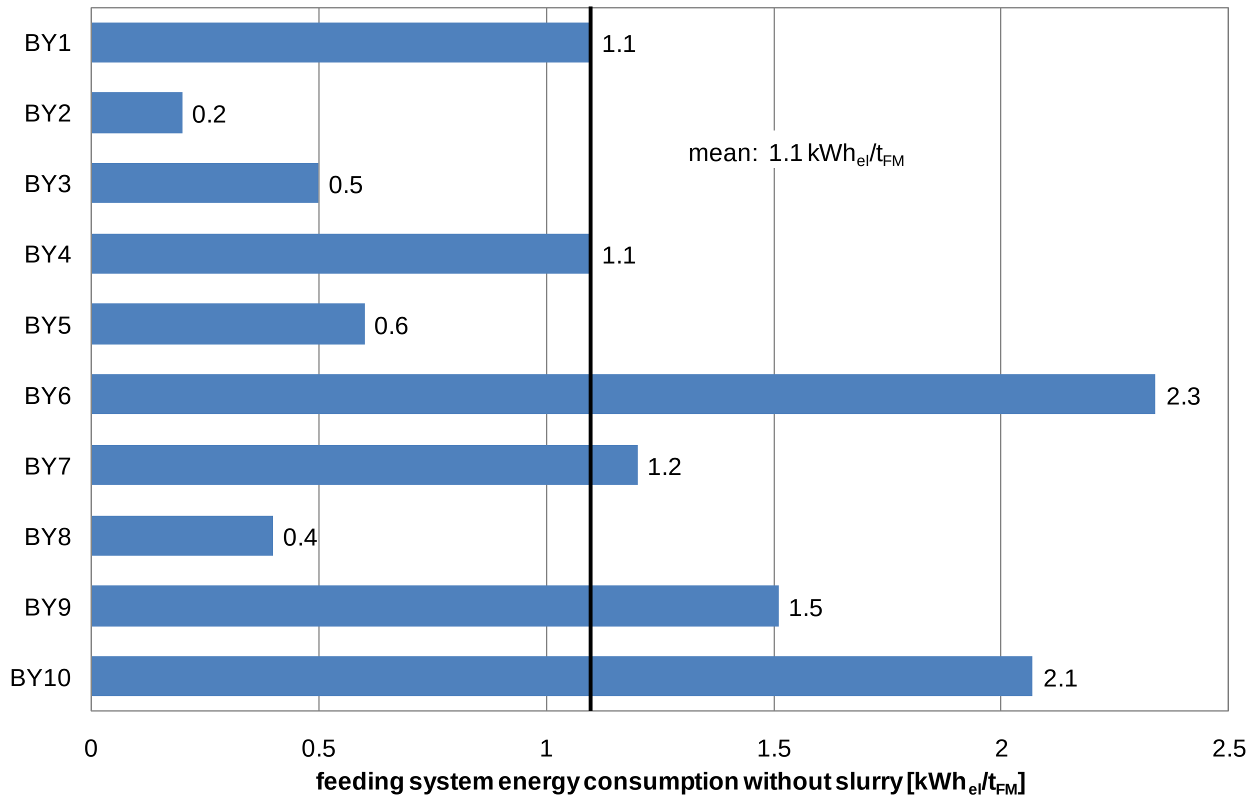


Figure 4.17: Specific feeding system electric energy consumption for solid feedstock

The identified range of 0.2...2.3 kWh$_{el}$/t$_{FM}$ can be explained with the different number of screws used at the various feeding systems. As a result, feeding systems have potential for optimisation by avoiding unnecessary components such as screw-conveyors.

4.3.5 Stirring System

The specific stirring electric energy consumption in relation to the added substrate mass varies between 1.9 kWh$_{el}$/t$_{FM}$ and 12.6 kWh$_{el}$/t$_{FM}$ (Figure 4.18). It fluctuates very much and can be traced back to the different hydraulic retention times of the plants. In some cases, high specific stirring electric energy consumptions correlate with a high DM-content (Figure 4.19). However, a direct interaction of the specific stirring electric energy consumption with the active digester volume and the DM-content cannot be identified.

Every biogas plant has different requirements regarding the process of mixing, depending on the risk of swimming and sinking layers. Several parameters, such as frequency and duration of stirring, type of stirring system and the substrates used, also have an impact on the specific stirring electric energy consumption.

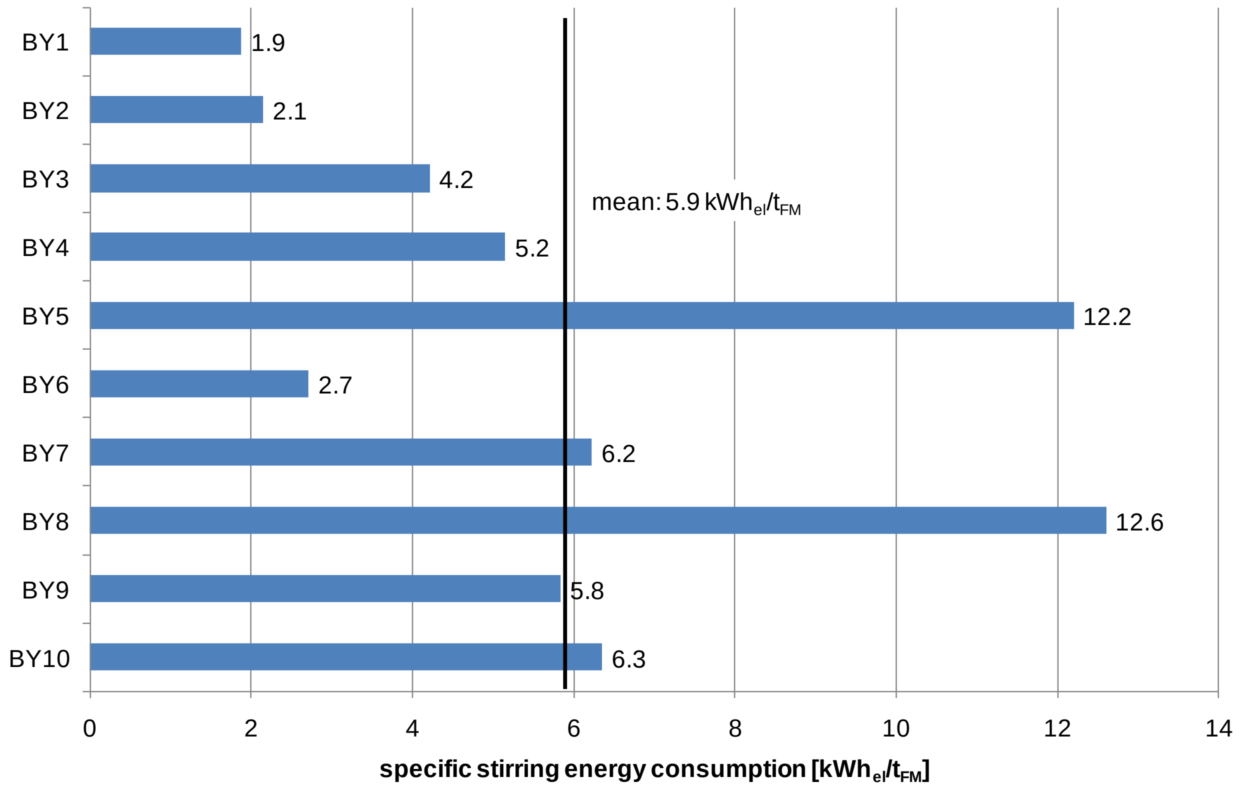


Figure 4.18: Specific stirring electric energy consumption in comparison to the fed substrate mass

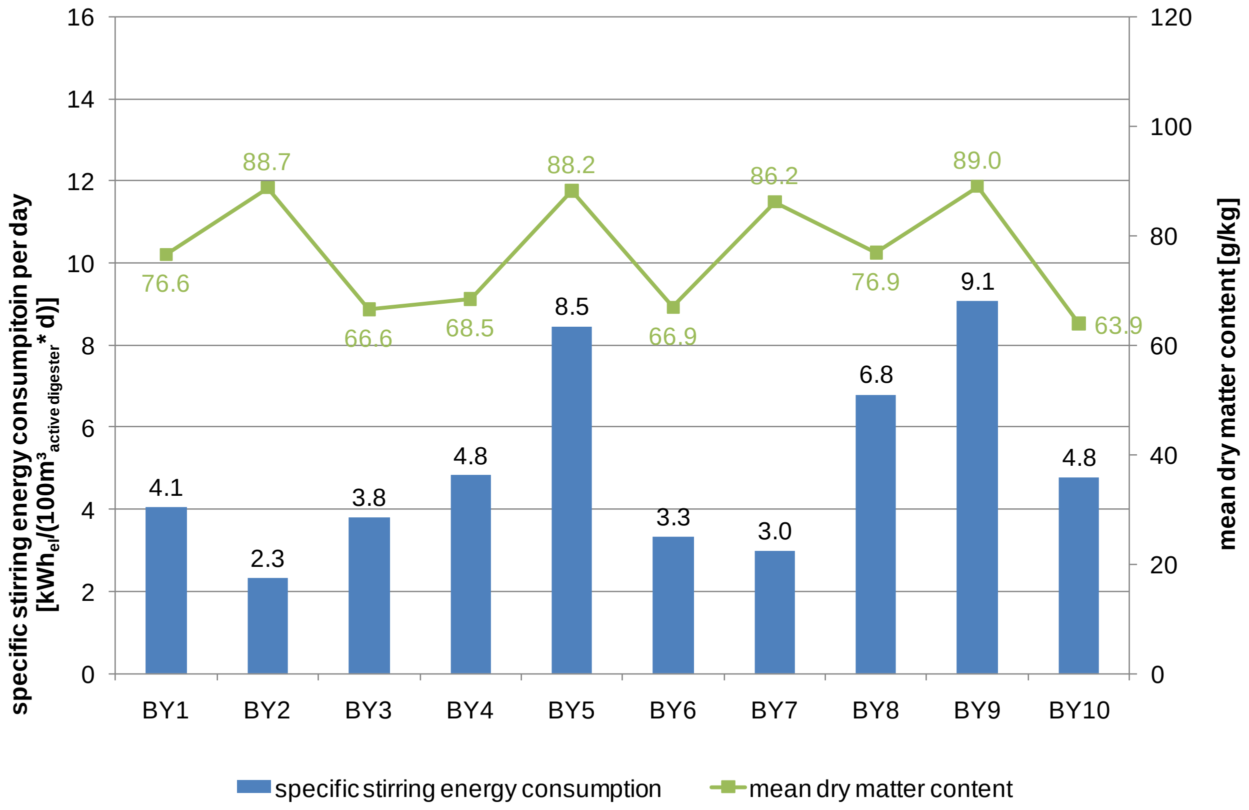


Figure 4.19: Specific stirring electric energy consumption in comparison to the mean dry matter content

Various stirring technologies are used to homogenise the added feedstock in the digester. In most cases, submergible motor mixers are utilised, also types such as paddle mixers, axial paddle mixers, stick mixers, and long axle mixers (Figure 4.20). The allocation of types correlates with the data in Fachagentur Nachwachsende Rohstoffe (2009c).

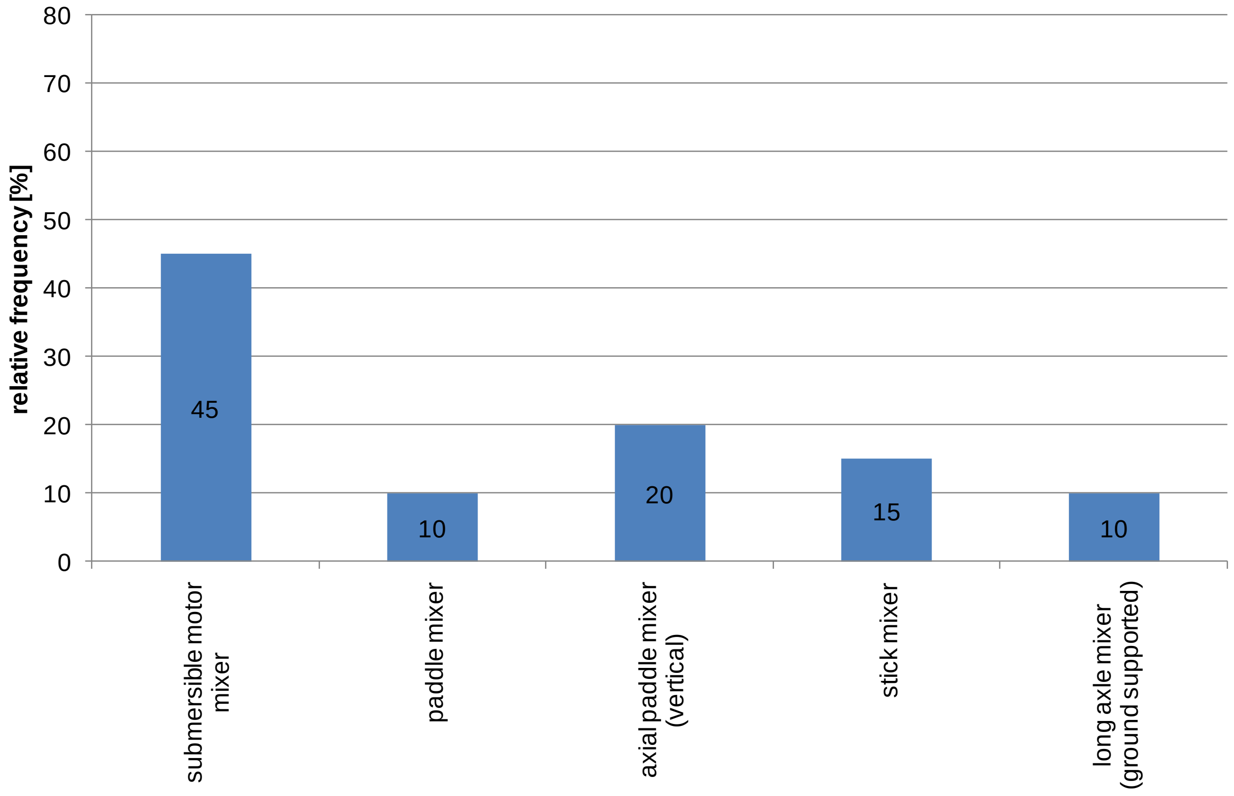


Figure 4.20: Stirring technologies used

4.3.6 Pump System

For the conveyance and recirculation of slurry and substrate, various type of pumps such as rotary-piston pumps (33 %), eccentric spiral pumps (27 %), centrifugal pumps (20 %), pulsating pumps (13 %) and submersible mulching pumps (7 %) are used (Figure 4.21).

This variation in pump type is due to the different conveyed substrates and applications, thus, a comparison is not possible. Frequently, biogas plants are equipped with overflows for which pumps are unnecessary. Besides this, some plants also have central pumping units.

The investigation reveals that rotary-piston pumps require a high degree of maintenance because the pistons need to be replaced every 3 to 6 months.

To minimise pumping expenses, overflows are preferable. However, to generate an ecological benefit, these overflows must be gas-tight.

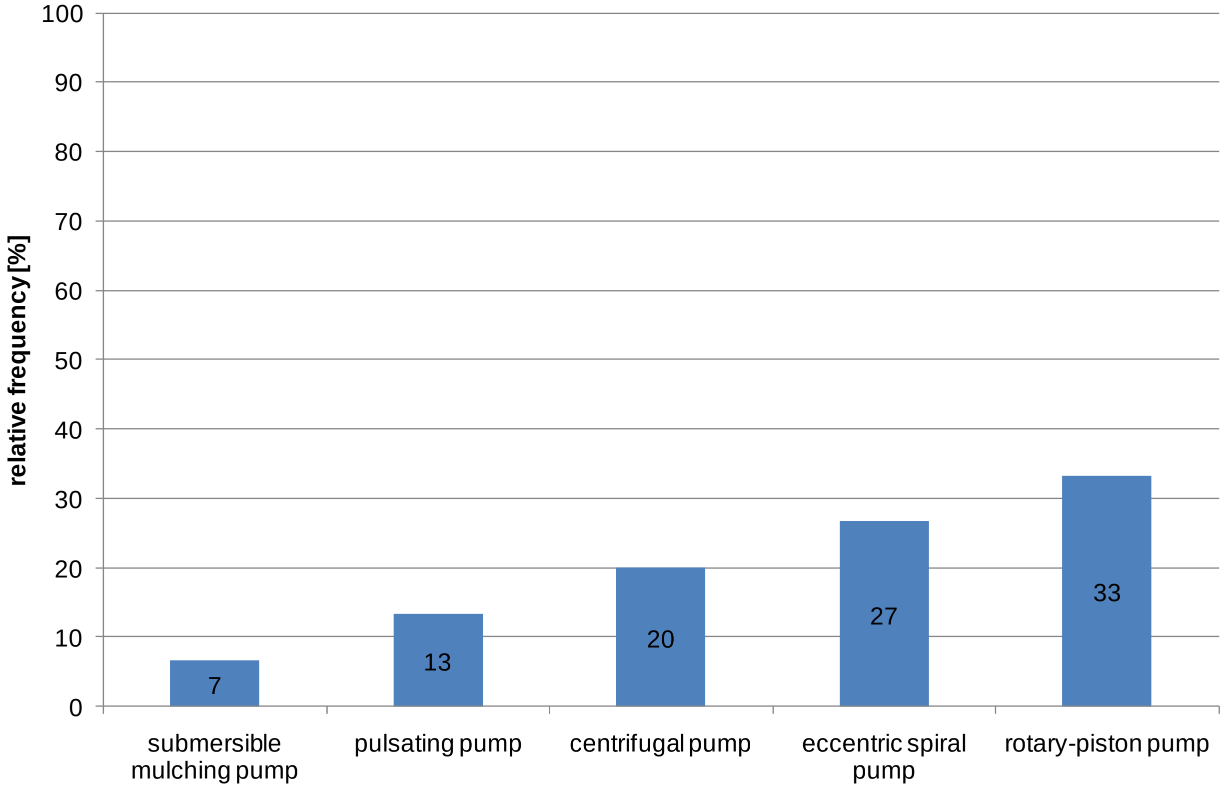


Figure 4.21: Pump technologies used

4.4 Gas Processing

Before the biogas can be combusted in the CHP-Unit, it needs to be cleaned. For this purpose, desulphurisation and dehumidification are necessary.

4.4.1 Desulphurisation

The level of H_2S in the investigated plants varies between 0 ppm and 308 ppm (Figure 4.22). However, in some cases it was not possible to take biogas samples directly upstream of the CHP-Unit. So these values are only approximations.

A concentration of less than 200 ppm H_2S is necessary for trouble-free operation (Fachagentur Nachwachsende Rohstoffe 2009c). This value is reached by 90 % of the investigated biogas plants.

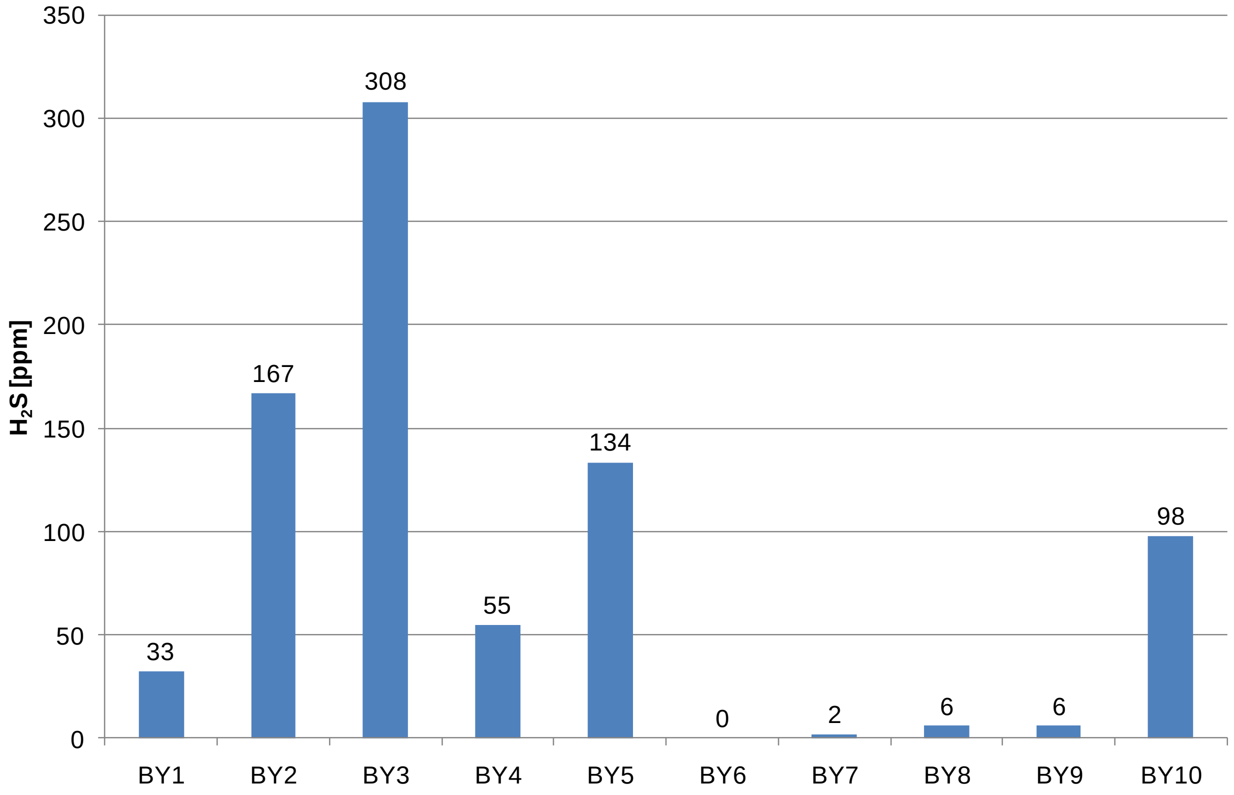


Figure 4.22: H_2S content of the investigated biogas plants

The air supply rate is normally maintained at a fixed rate in relation to the produced biogas. However, it is sometimes adjusted by the biogas plant operator depending on the particular H_2S content.

Upon closer inspection of the injected air content, it is found that a mean injection rate of 3.9 % is used for desulphurisation (Figure 4.23). The injected air rate of BY2 (no data available) and BY6 cannot be evaluated because of the use of air compressors, which are required for further applications such as running the pneumatic valves of pumping stations.

Among the analysed biogas plants, BY3 has the very high H_2S content of 308 ppm. There the air injection rate is only 1.9 %. Increasing the air injection rate will, however, lead to a reduced H_2S content.

A closer look at the biogas plants shows that the specific desulphurisation energy consumption via air injection varies between 0.02 $(kWh_{el}/d)/(Nm^3/h)$ and 0.42 $(kWh_{el}/d)/(Nm^3/h)$ (Figure 4.24). There is a high specific desulphurisation energy consumption in the smaller biogas plants. This cannot be attributed to a higher air injection rate, but can be traced back to inadequate dimensioning and design of the air injection system.

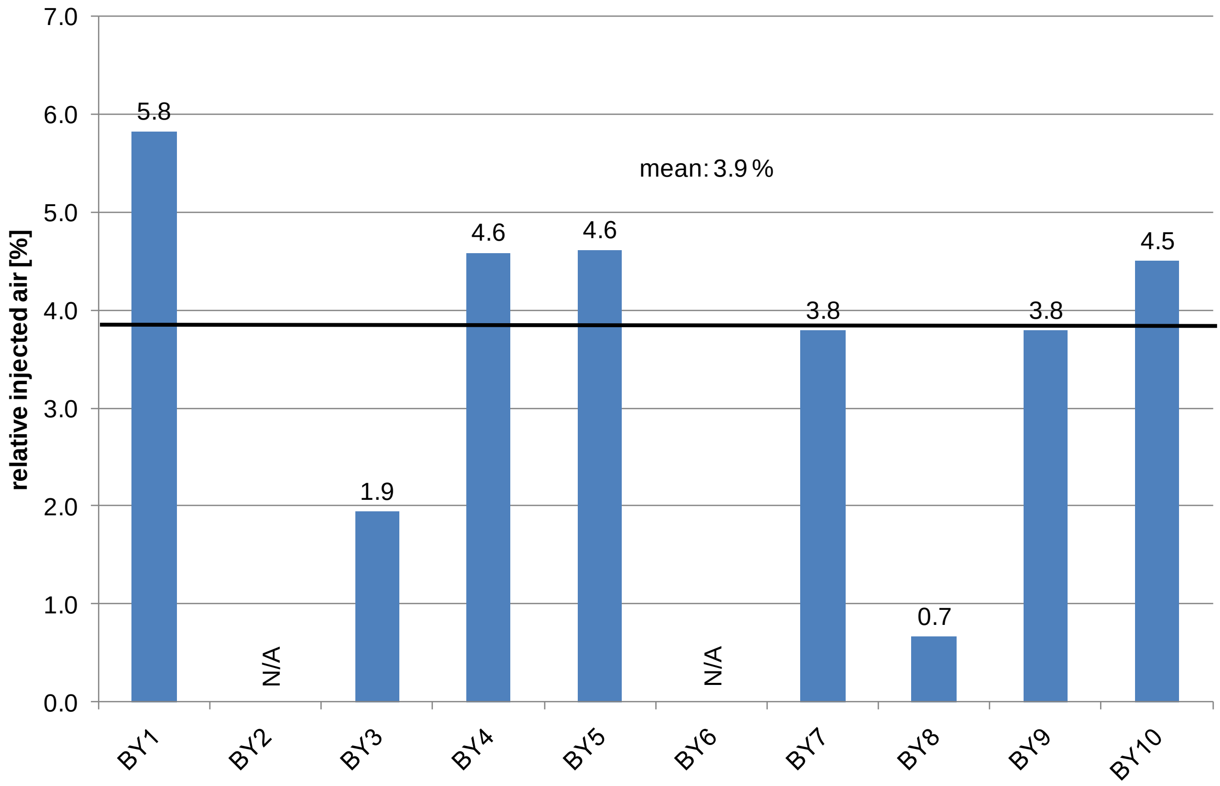


Figure 4.23: Injected air rate for desulphurisation of the investigated biogas plants

The biological desulphurisation of the biogas plants BY1 and BY6 is carried out via air compressors which show a significantly higher energy consumption than normal desulphurisation air blowers.

Due to the range in fluctuations, there is clearly a high potential for the reduction of the desulphurisation energy consumption.

4.4.2 Dehumidification

The dehumidification of biogas is carried out in two different ways (Figure 4.25). Passive underground cooling systems are the most common technology (70 %) to dehumidify biogas; however, active gas cooling units are also used (30 %).

Figure 4.26 shows the length of each passive underground cooling system. A large variation of distance can be seen.

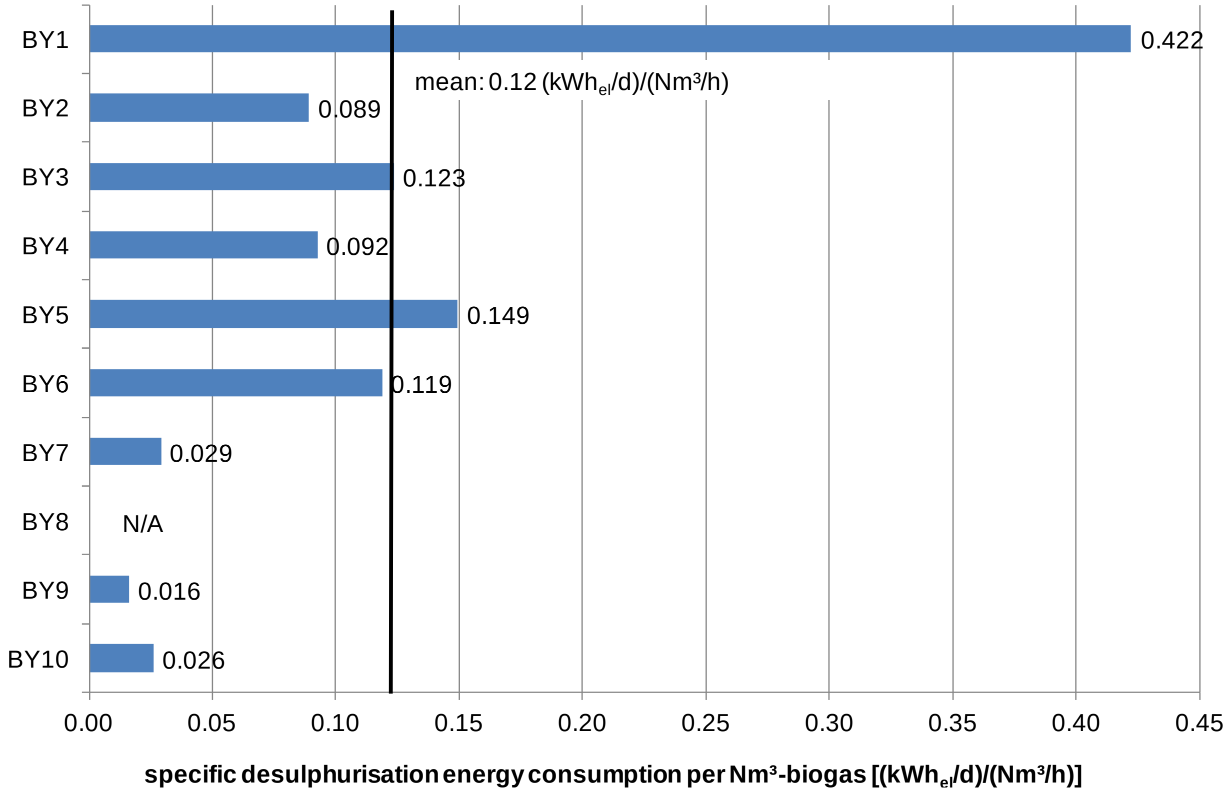


Figure 4.24: Specific desulphurisation electric energy consumption of the investigated biogas plants

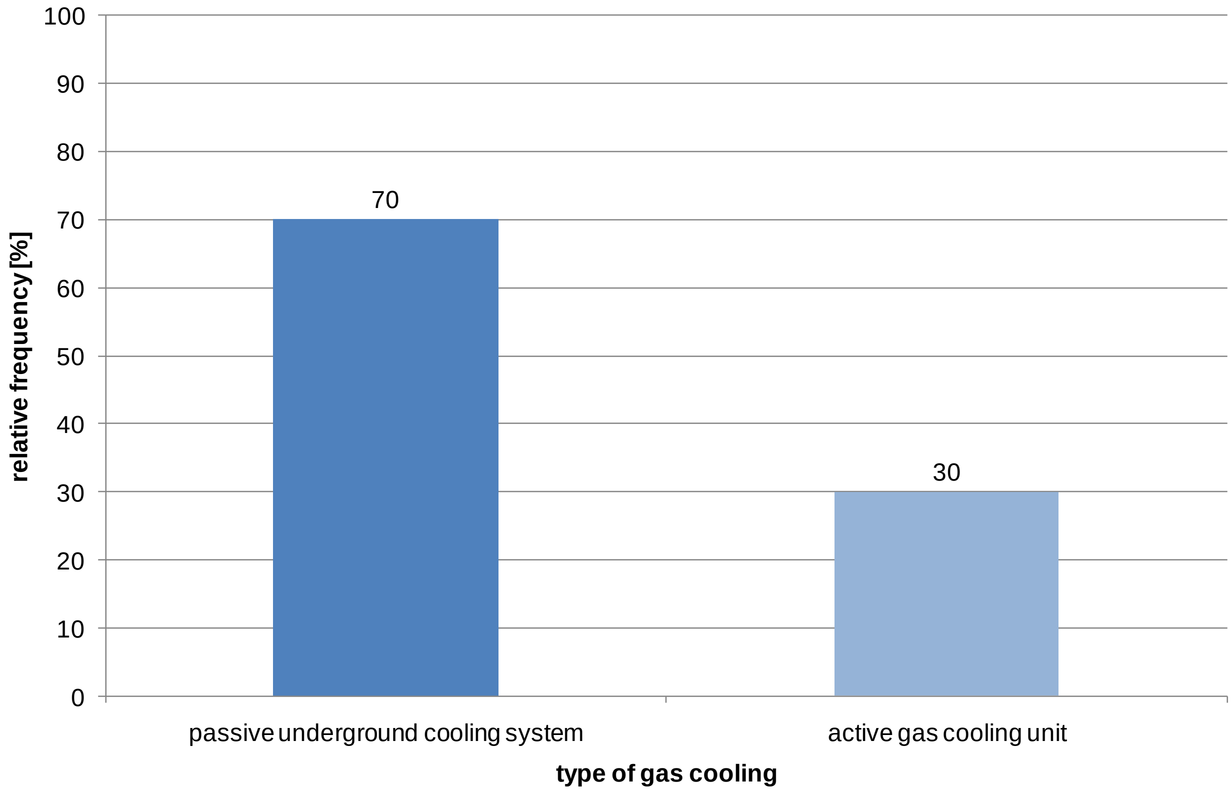


Figure 4.25: Used gas cooling technology of the investigated biogas plants

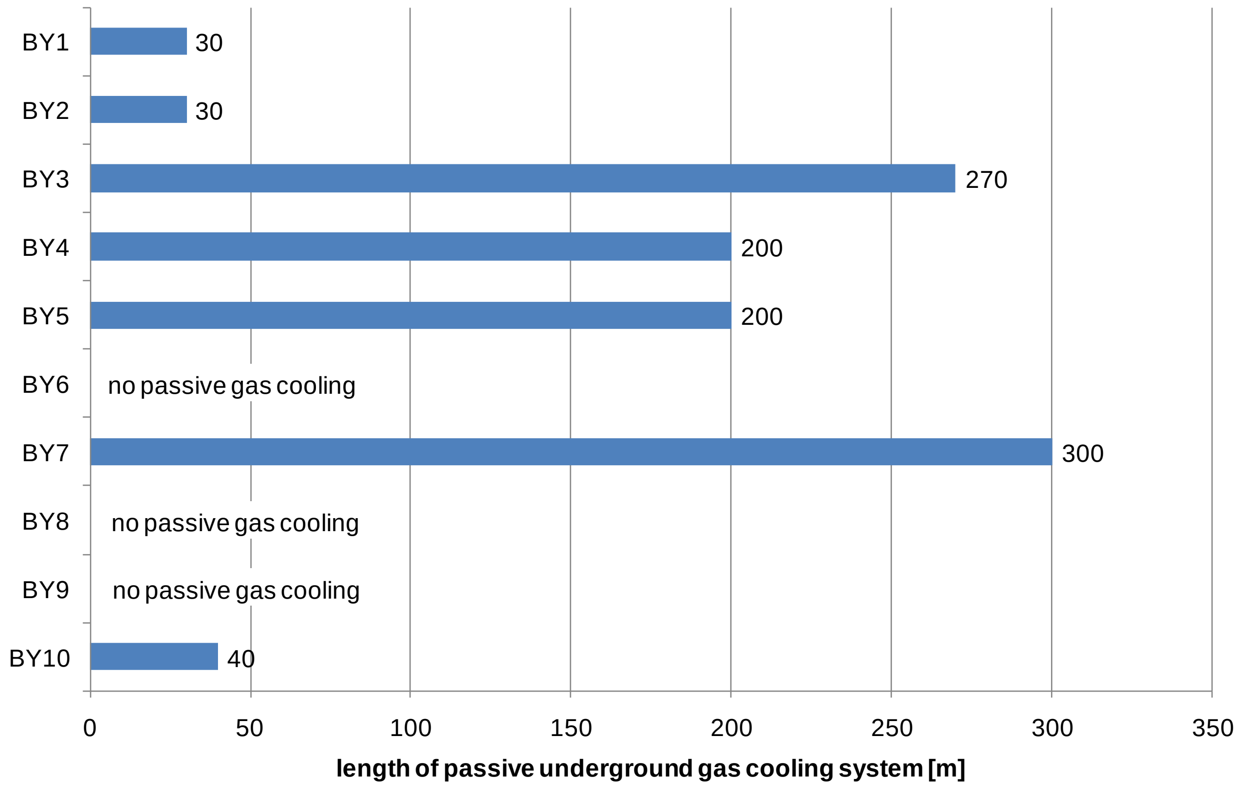


Figure 4.26: Length of passive underground cooling system

The specific active cooling unit electric energy consumption per electric capacity of the CHP-Unit is shown in Figure 4.27. The values vary between 0.14 $(kWh_{el}/d)/kW_{el}$ and 0.20 $(kWh_{el}/d)/kW_{el}$. Because of the wide range of electric energy consumption, a potential for optimisation is expected. However, because of the low amount of measurement data, these values cannot be assumed as representative.

4.5 Biogas Utilisation

4.5.1 Gasholder

The storage capacity for biogas varies between 100 m³ and 1,250 m³ (Figure 4.28). In some cases, the gasholder volume cannot be accurately determined because of fluctuating substrate-fill levels of the digesters. Furthermore, correlations between electric capacity of the biogas plant and its biogas storage capacity cannot be identified.

Figure 4.29 shows the maximum period for storing biogas with regard to the calculated biogas volume flow. The maximum period for storing biogas varies between 0.4 h and 15.6 h.

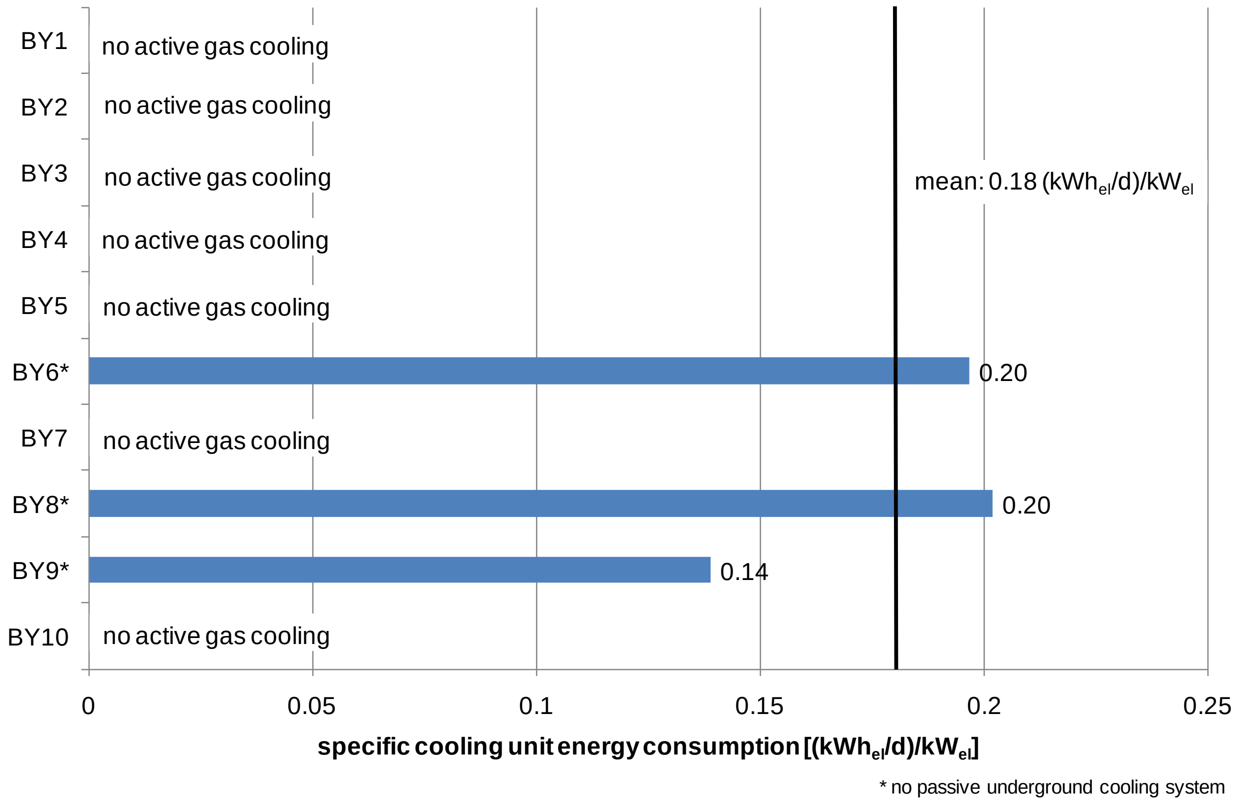


Figure 4.27: Specific cooling unit electric energy consumption per electric capacity of the CHP-Unit

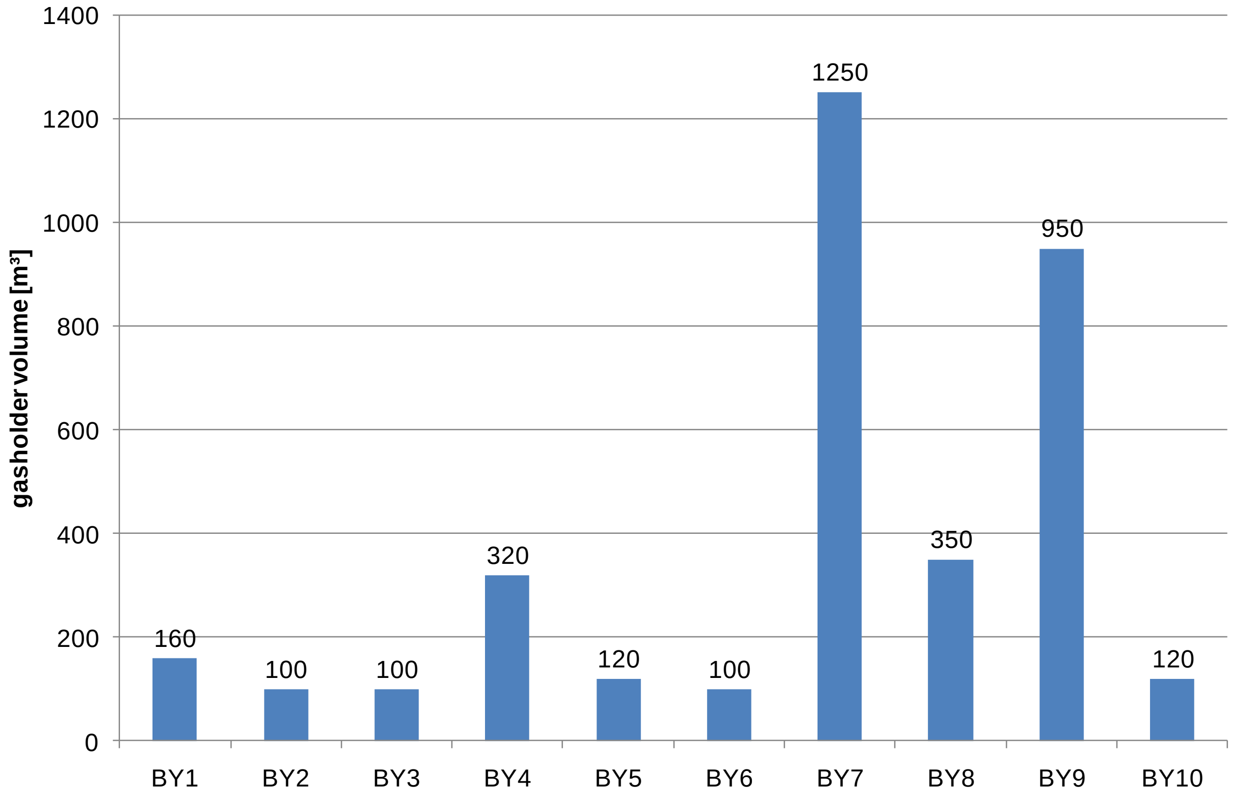


Figure 4.28: Storage capacity for biogas of the investigated biogas plants

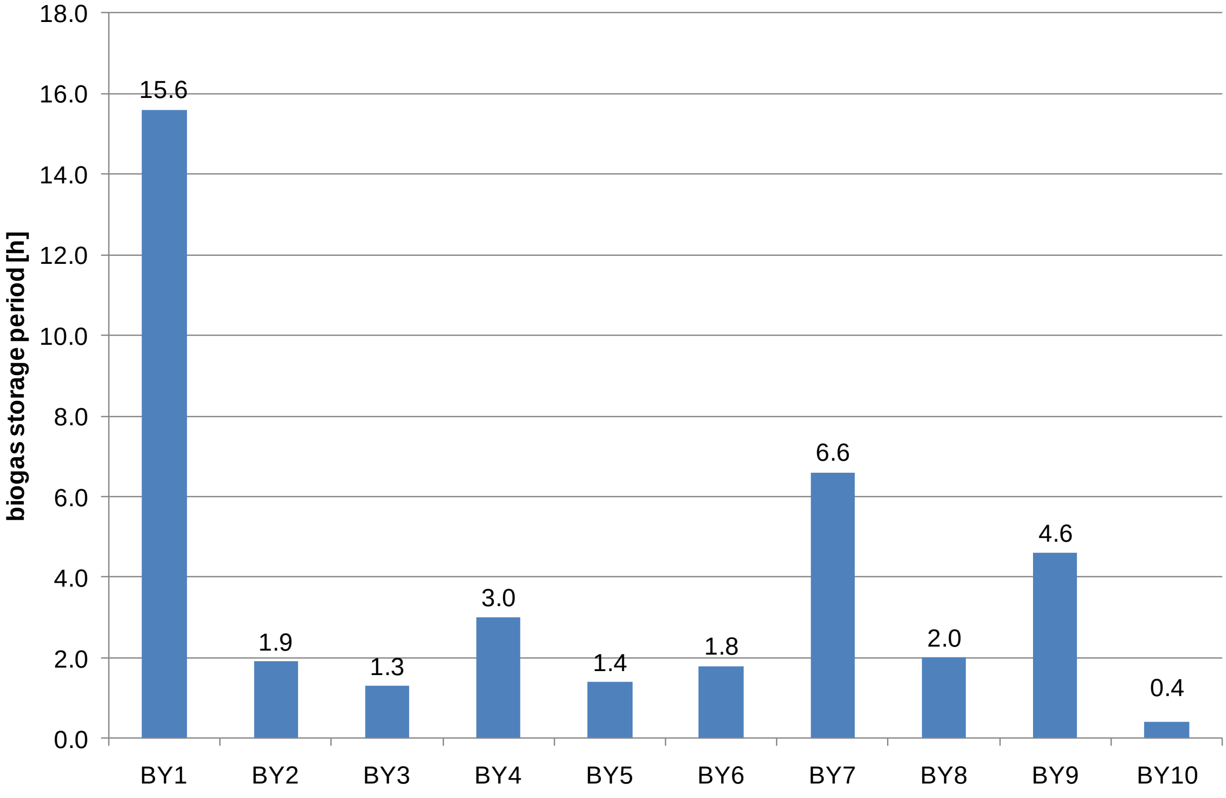


Figure 4.29: Maximum biogas storage period of the investigated biogas plants

During standard plant operation, a gasholder-fill level of 75 % is assumed. So, if the CHP-Unit malfunctions, the gasholder capacity is reached after an average period of 55 min. However, biogas plant BY10 reaches its maximum gasholder capacity already after 6 min. After the gasholder capacity is reached, the excess biogas is not used and exhausted to the atmosphere or combusted in a gas flare.

Due to this, maintenance should be carried out in times when the biogas storage has enough capacity in order to avoid biogas losses. Furthermore, the minimum size of biogas storage has to accommodate about 20...50 % of the daily produced amount of biogas (Bayerisches Landesamt für Umwelt 2007).

4.5.2 CHP-Unit

Figure 4.30 shows the two different types of engines for CHP-Units used in Bavaria. The electric capacity of the pilot-injection CHP-Units varies between 30 kW_{el} and 80 kW_{el}, whereas the capacity of the gas engine CHP-Units is between 100 kW_{el} and 526 kW_{el}.

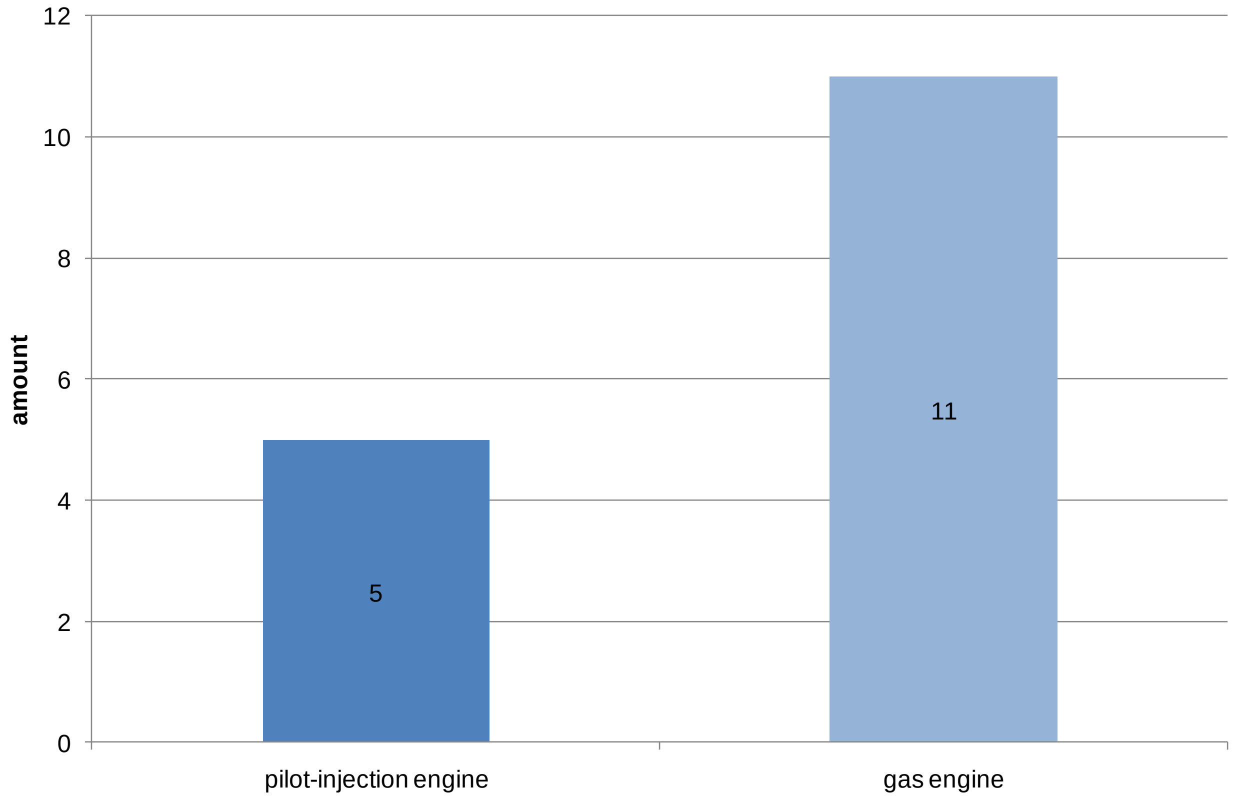


Figure 4.30: Engines used for CHP-Units of the investigated biogas plants

The electric efficiency of the CHP-Units is shown in Figure 4.31. Gas engine CHP-Units have an electric efficiency from 33.3 % to 40.4 %. The electric efficiency of pilot-injection CHP-Units varies from 32 % to 37 %. Because of the lack of the manufacturer´s information, the electric efficiency of BY1 (32 %) is assumed.

4.5.3 CHP-Unit Usage Rate

The theoretical usage rate of the CHP-Units is shown in Figure 4.32. It is notable that these values vary from 80 % to 98 %. The low usage rate of BY1 and BY6 can be attributed to old CHP-Units and negligence in plant operation.

High theoretical CHP-Unit rates demonstrate successful operation of biogas plants and adequate dimensioning of the CHP-Unit(s). However, very high usage rates must be considered critical, because of potential overload and biogas losses to the atmosphere.

The highest usage rates of 98 % can be found at BY7 and BY10.

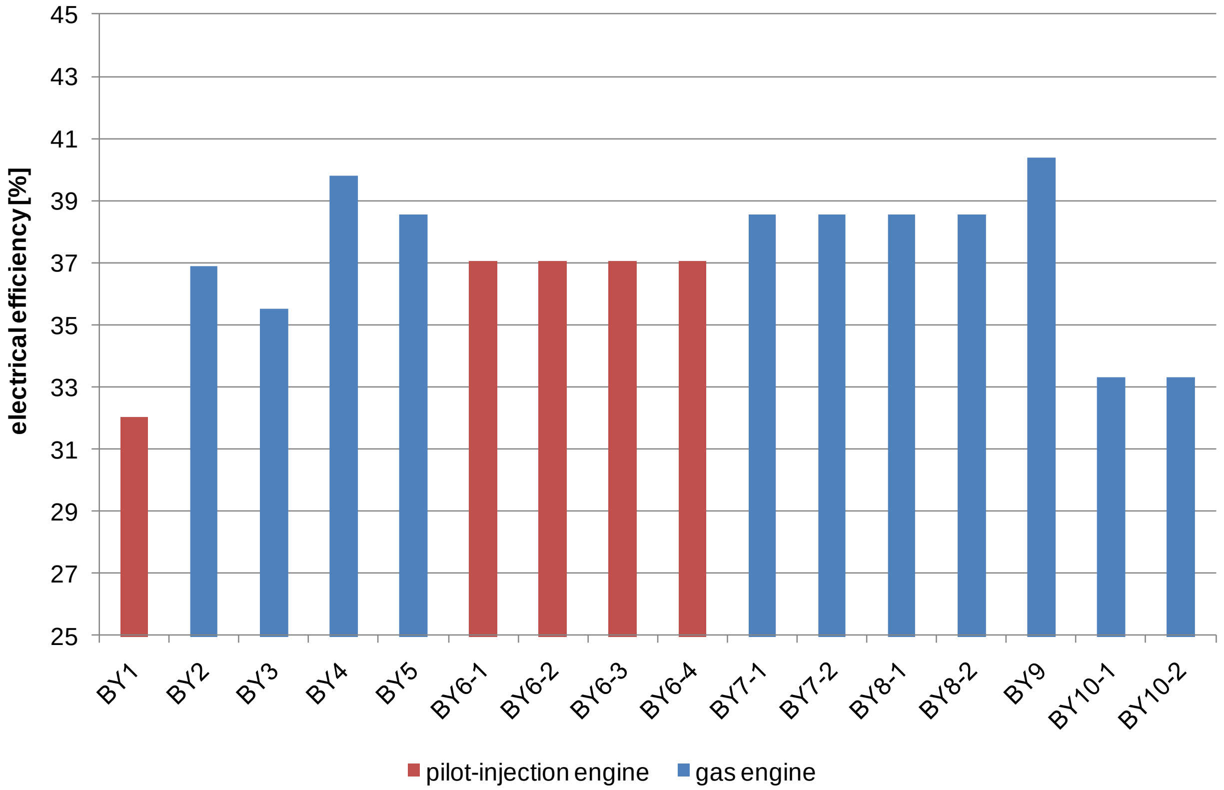


Figure 4.31: Electric efficiency of the CHP-Units

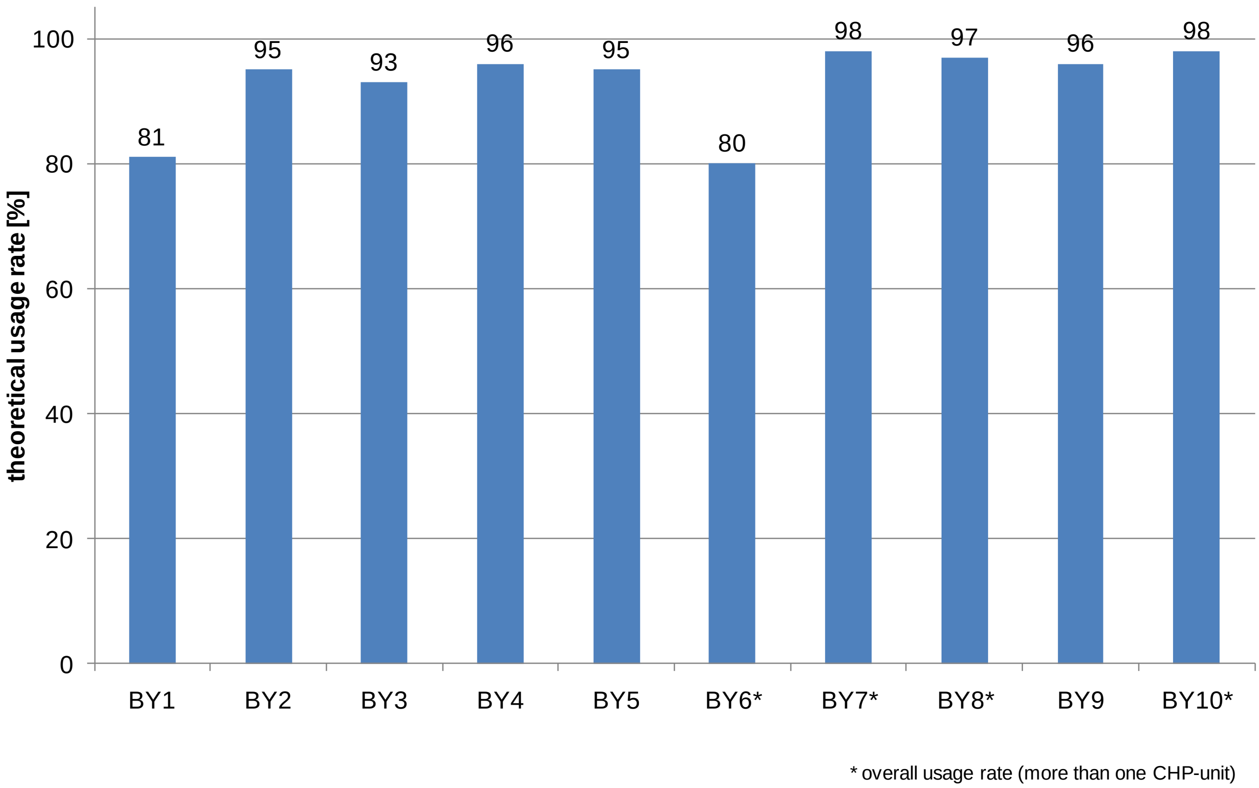


Figure 4.32: CHP-Usage rate of the investigated biogas plants

4.5.4 Heat Utilisation

Figure 4.33 shows the heat utilisation of the investigated biogas plants. Both, the process heat and the utilised heat (cogeneration-bonus) are considered. If the amount of process heat is not measured, 12.5 % of the produced heat is assumed.

Only 50 % of the 10 biogas plants utilise heat and receive the cogeneration bonus. The mean utilised heat quantity is just 34.2 %, only BY7 uses all the produced heat.

The low heat utilisation shows high potential for optimisation.

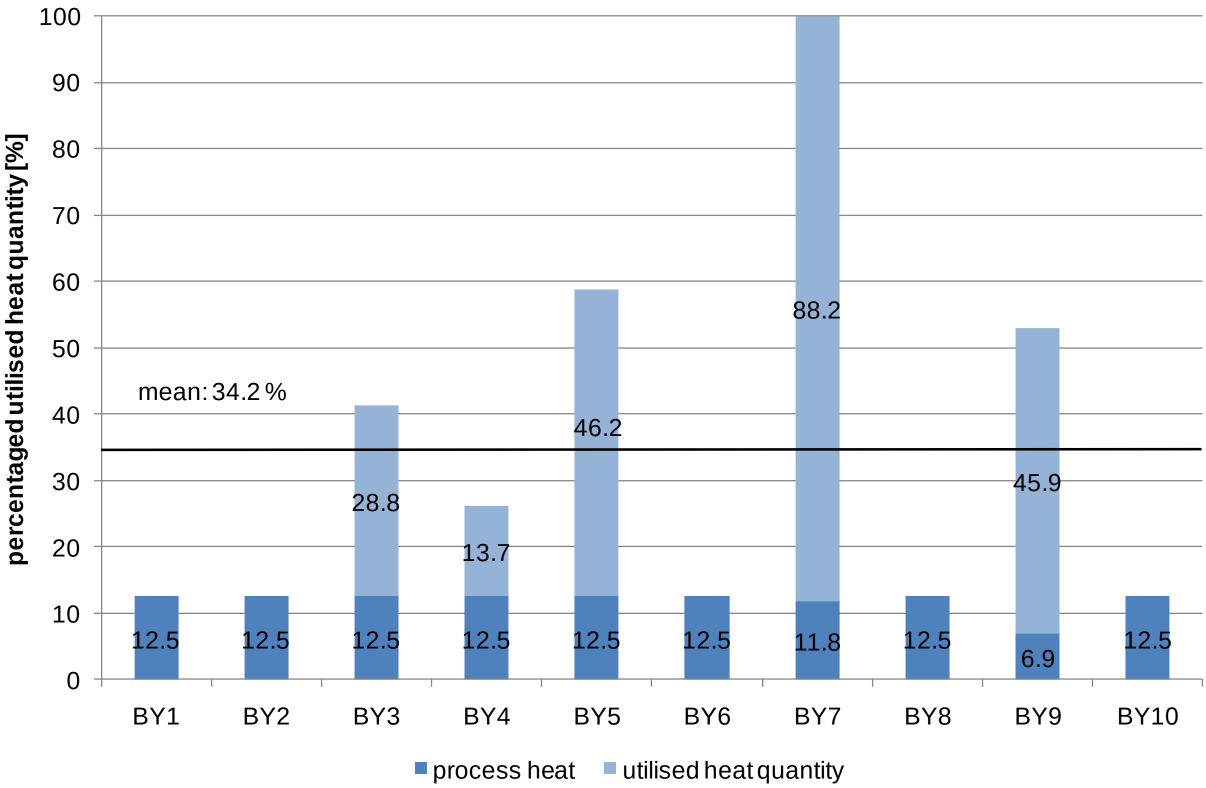


Figure 4.33: Heat utilisation of the investigated biogas plants

Upon closer inspection of the heat consumers, it is found that in most cases the owner`s residential buildings or farm buildings (45 %) are heated. Sometimes, the heat is also used for drying wood chips (25 %). Local heat distribution networks are found in 25 % of all biogas plants. However, these distribution networks are small and supply only a few buildings (Figure 4.34). The sale of heat to external costumers is not apparent. Despite the utilisation of heat at all biogas plants, excluding BY8, the biogas plants BY1, BY2, BY6 and BY10 do not claim for the cogeneration bonus.

As the utilisation of heat is low, it has a very high potential to improve the ecology and economy of the plants.

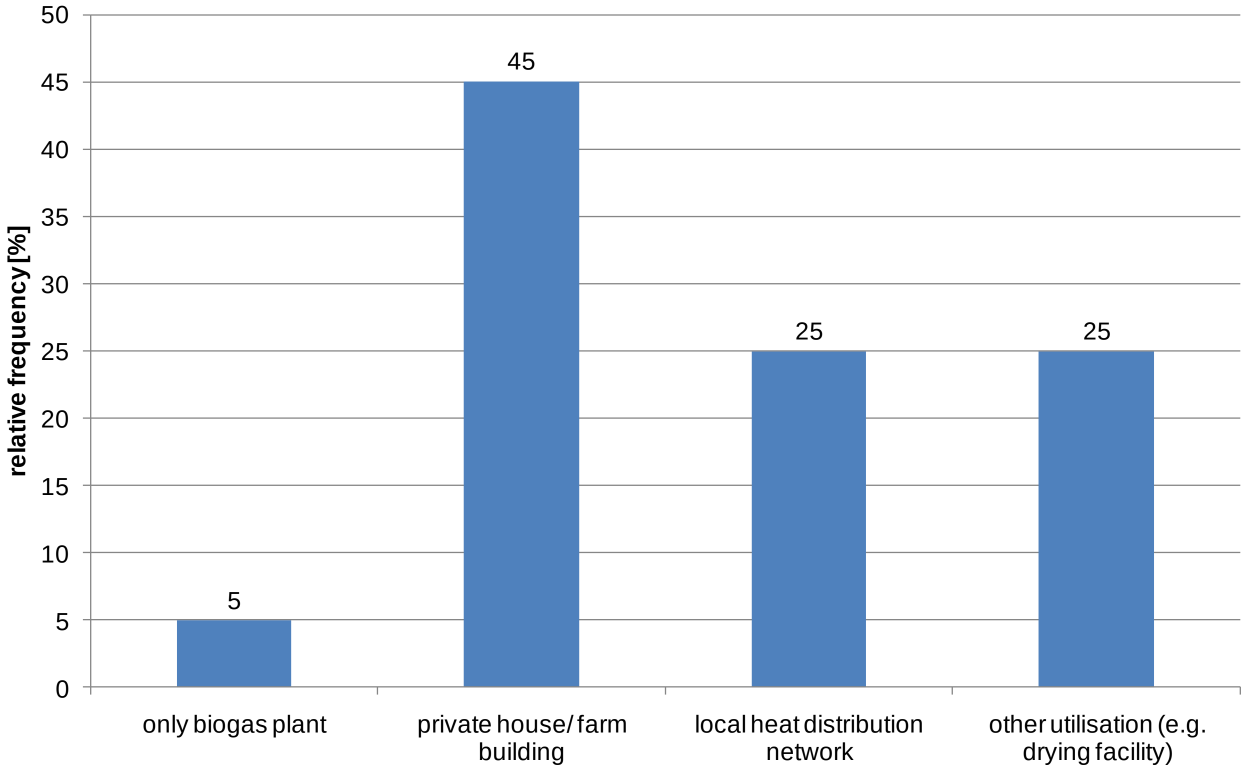


Figure 4.34: Heat consumers of the investigated biogas plants

4.6 Measurement and Control Technology

4.6.1 Documentation

Figure 4.35 shows the recording method of the operational log. Most of the operational logs are recorded by hand (50 %) or digitally recorded by hand (40 %), only a single operational log is recorded automatically.

The relative frequency of recordings is shown in Figure 4.36. Many biogas plant operators record data only once a year. This cannot result in high-quality recordings and is not to be recommended.

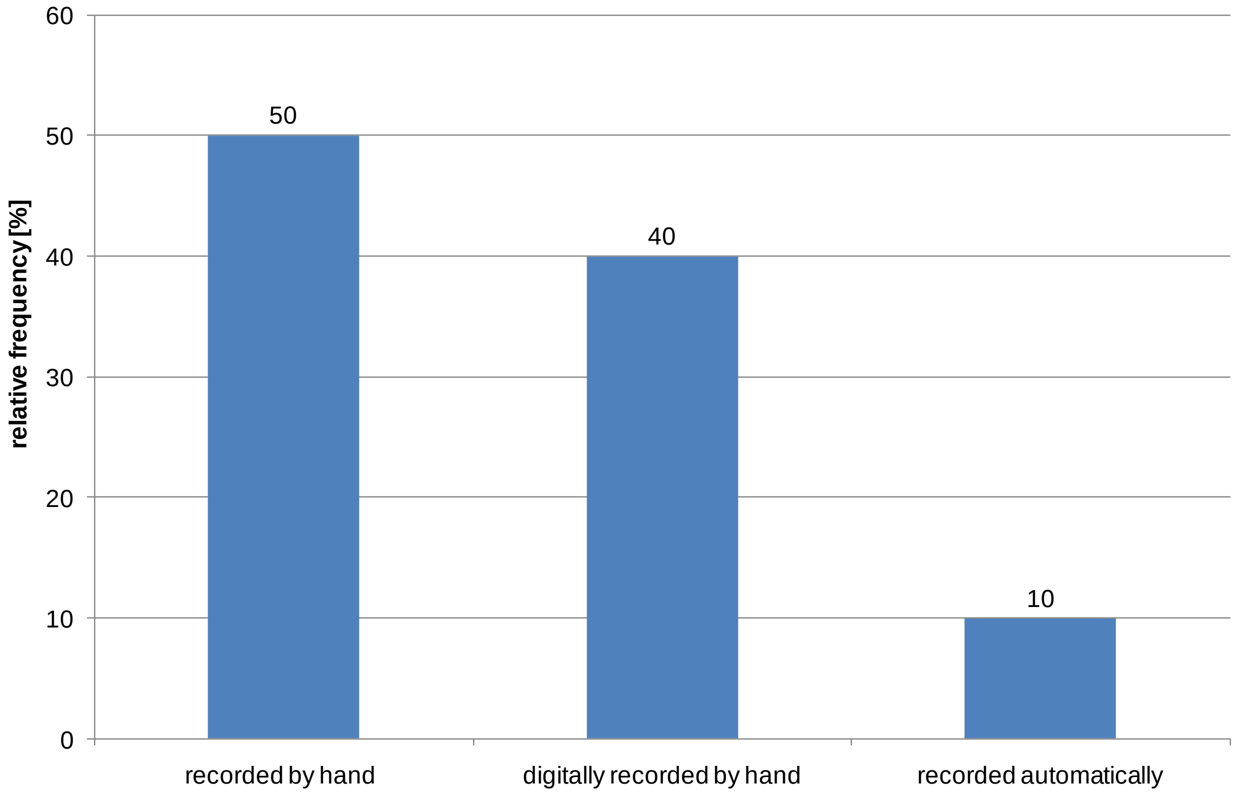


Figure 4.35: Recording method of operational logs

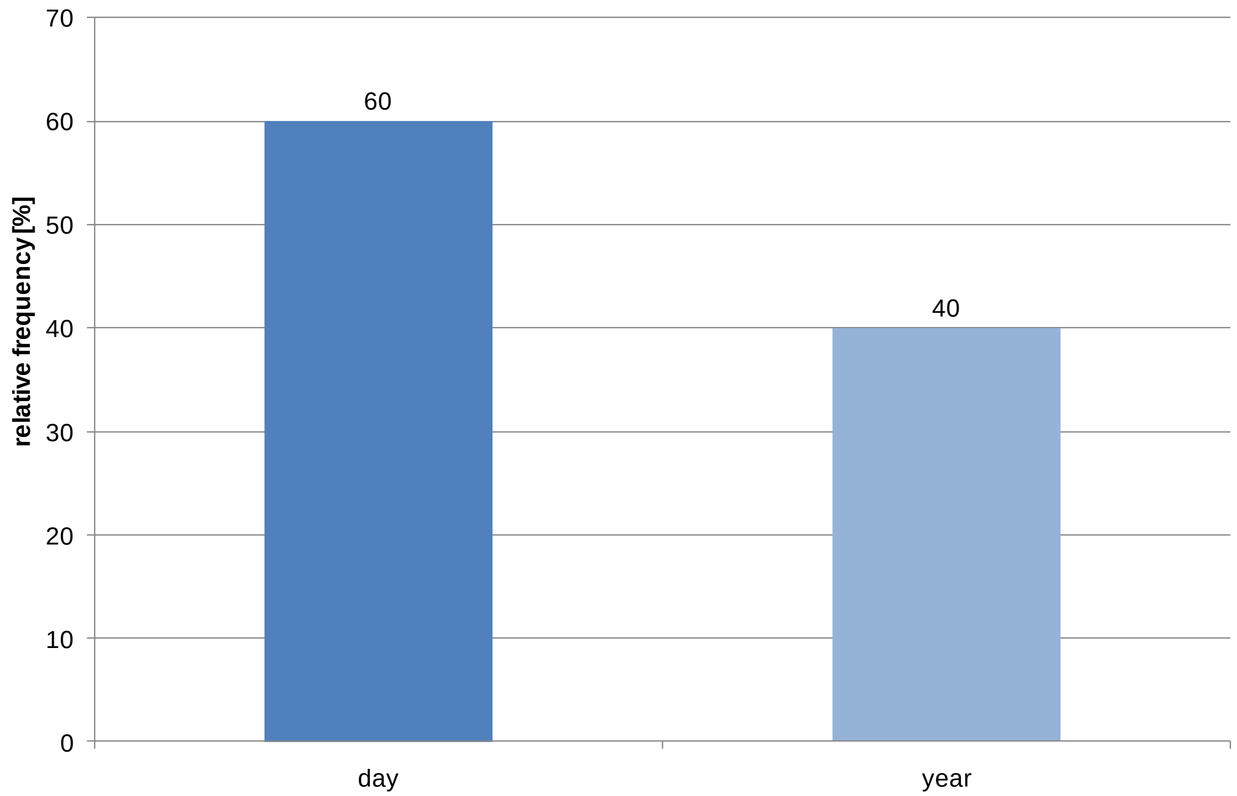


Figure 4.36: Relative frequency of recordings in the operational logs

4.6.2 Measurements

4.6.2.1 Substrate

A feeding system integrated weighing system is only used in BY6, BY7 and BY9. Biogas plant BY3 and BY10 utilise a front loader integrated weighing system. The lack of weighing systems adversely affects the quality of documentation and, thus, control of the daily amount of substrate added is not possible. This also affects the monitoring quality of the biochemical process.

The relative frequency of on-site measurements to control the biochemical process is shown in Figure 4.37. The available equipment varies at each biogas plant. It can be seen that on-site measurements have to be implemented and recorded more extensively in the future in order to get more information about the plant operation.

The frequency of external tests is shown in Figure 4.38. 95 % of the biogas plant operators carry out external tests regarding the biochemical process, however, the frequency of tests is insufficient with sample periods of up to one year.

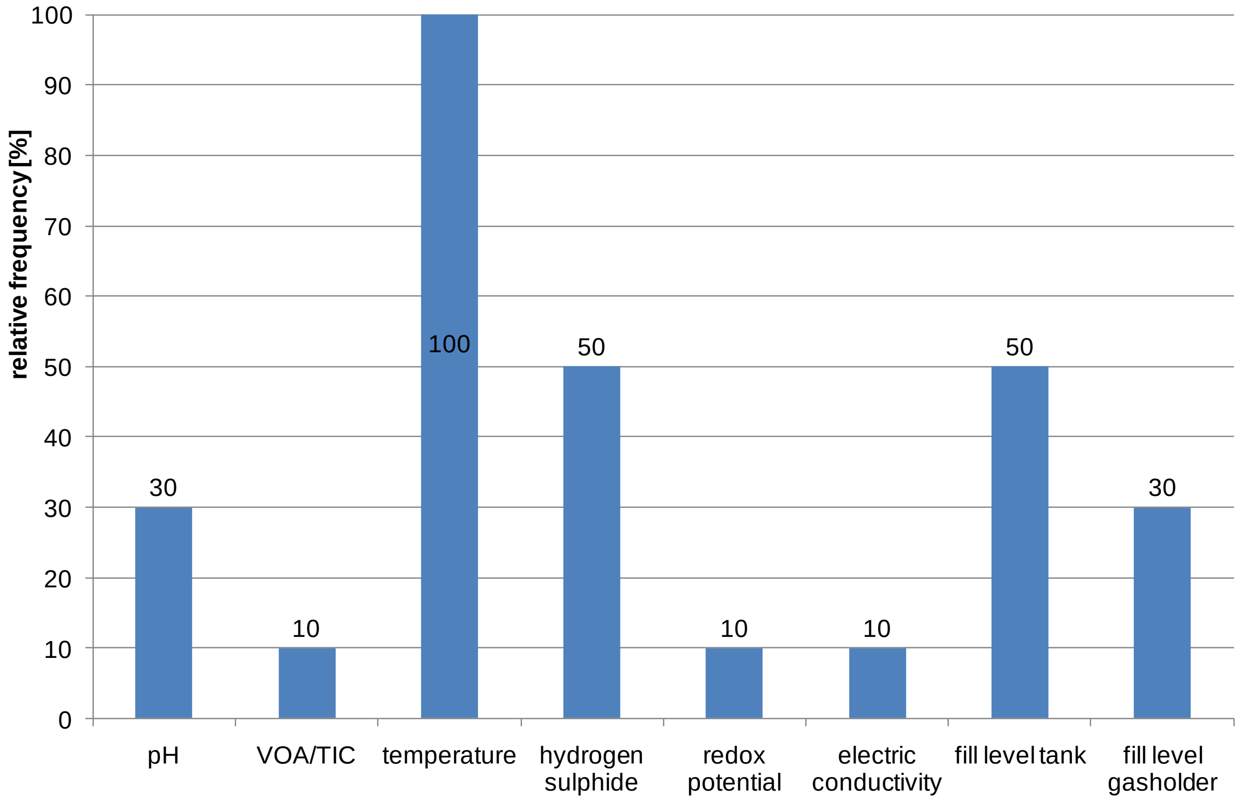


Figure 4.37: Relative frequency of onsite-measurements to control the biological process

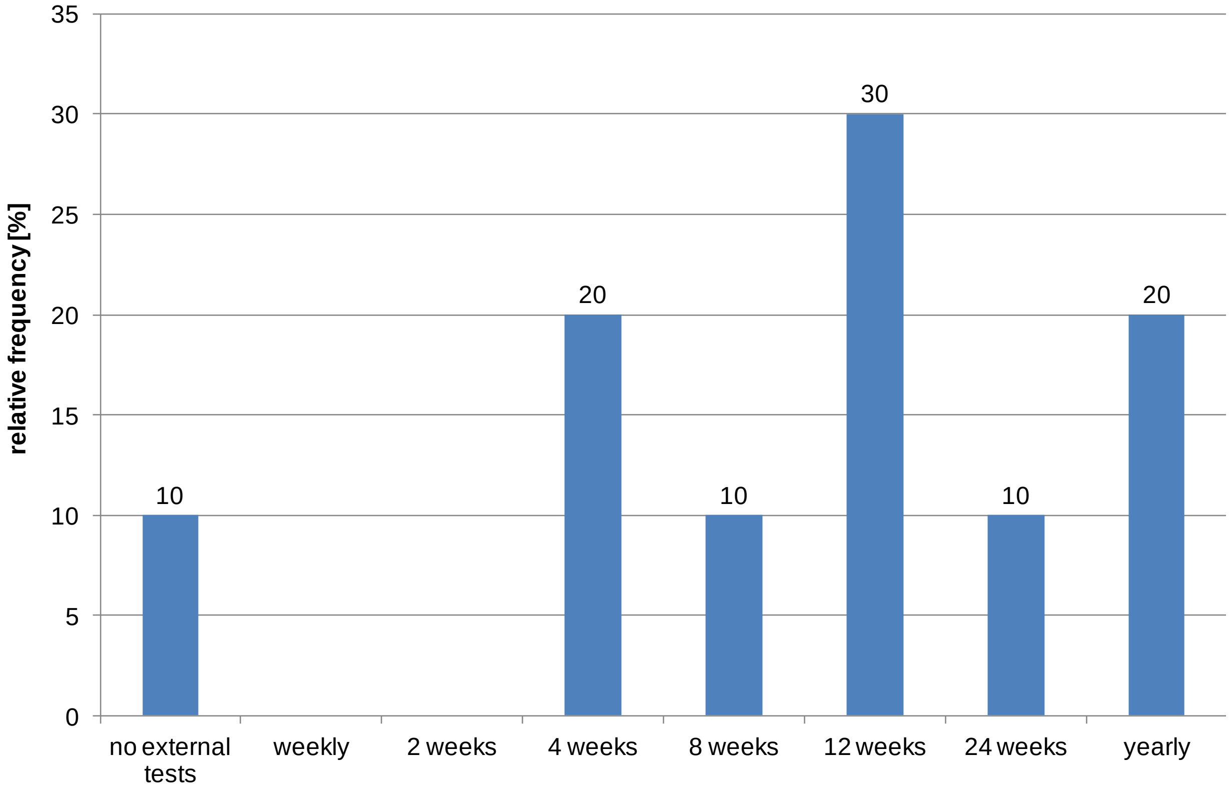


Figure 4.38: Relative frequency of external tests

4.6.2.2 Biogas Analysis

The composition of biogas can indicate problems of the biochemical process. Therefore, it is very important to analyse the components of the biogas produced. However, the composition of biogas is not measured at all biogas plants. Four biogas plants analyse the produced biogas regarding its content of methane, carbon dioxide, hydrogen sulphide and oxygen, only BY9 completely analyses its biogas (Figure 4.39).

4.6.2.3 Parasitic Energy Measurement

Figure 4.40 shows the relative frequency of biogas plants measuring the parasitic energy. Only 40 % of the investigated biogas plants record the parasitic electric energy and only 10 % measure the process heat demand.

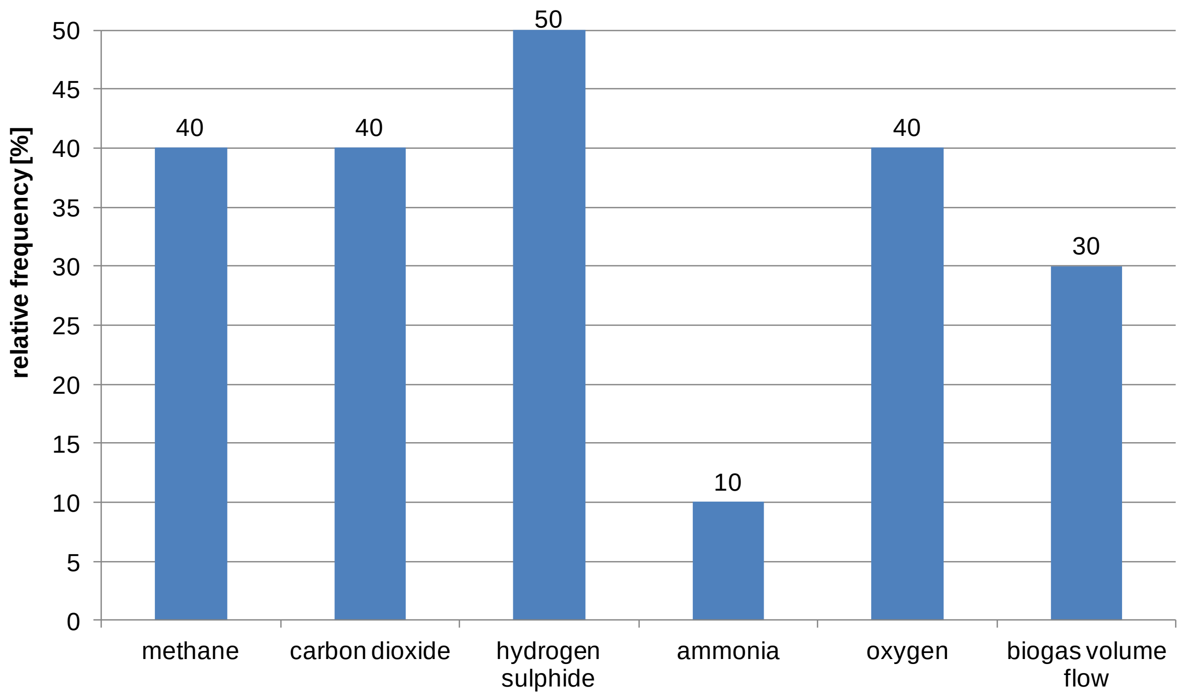


Figure 4.39: Measurement of the composition of biogas

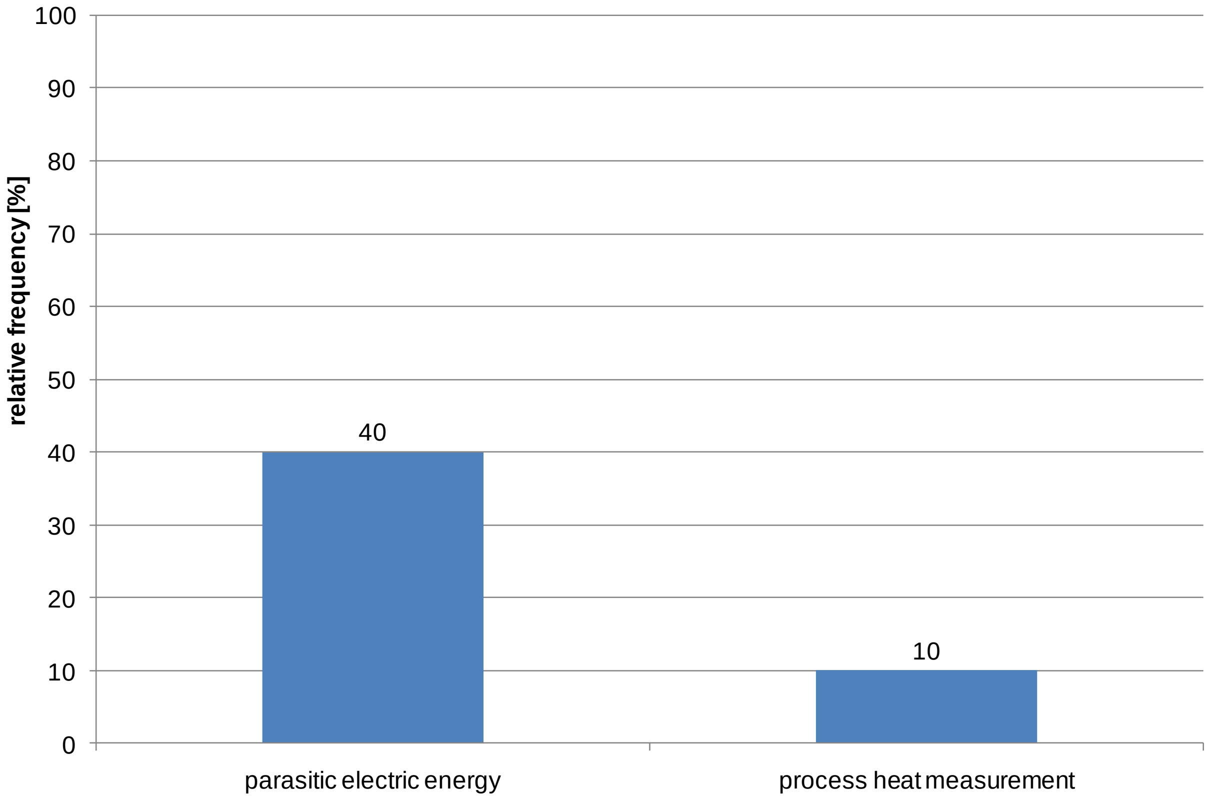


Figure 4.40: Measurement of parasitic energy consumption (electricity and heat)

4.7 Parasitic Electric Energy

Figure 4.41 shows the parasitic electric energy of the 10 biogas plants. The electricity consumption of each biogas plant is measured and compared to the gross electric energy production. Within this analysis, the parasitic electric energy is subdivided into two categories: the demand for the biogas production and the demand for the CHP-Unit.

The biogas production process contains a number of electric consumers such as the feeding system, stirrers, pumps, gas processing and circulation pumps for heating the digester. The CHP-Unit contains electric consumers such as a gas compressor, a primary / secondary pump, an emergency cooler, a charge air cooler and a room ventilator.

The parasitic electric energy of the 10 biogas plants varies from 4.7 % (BY2) to 7.5 % (BY6). The proportion of the mean CHP-Unit electric energy consumption is 2.8 % whereas 3.4 % is the average needed to run the components for biogas production.

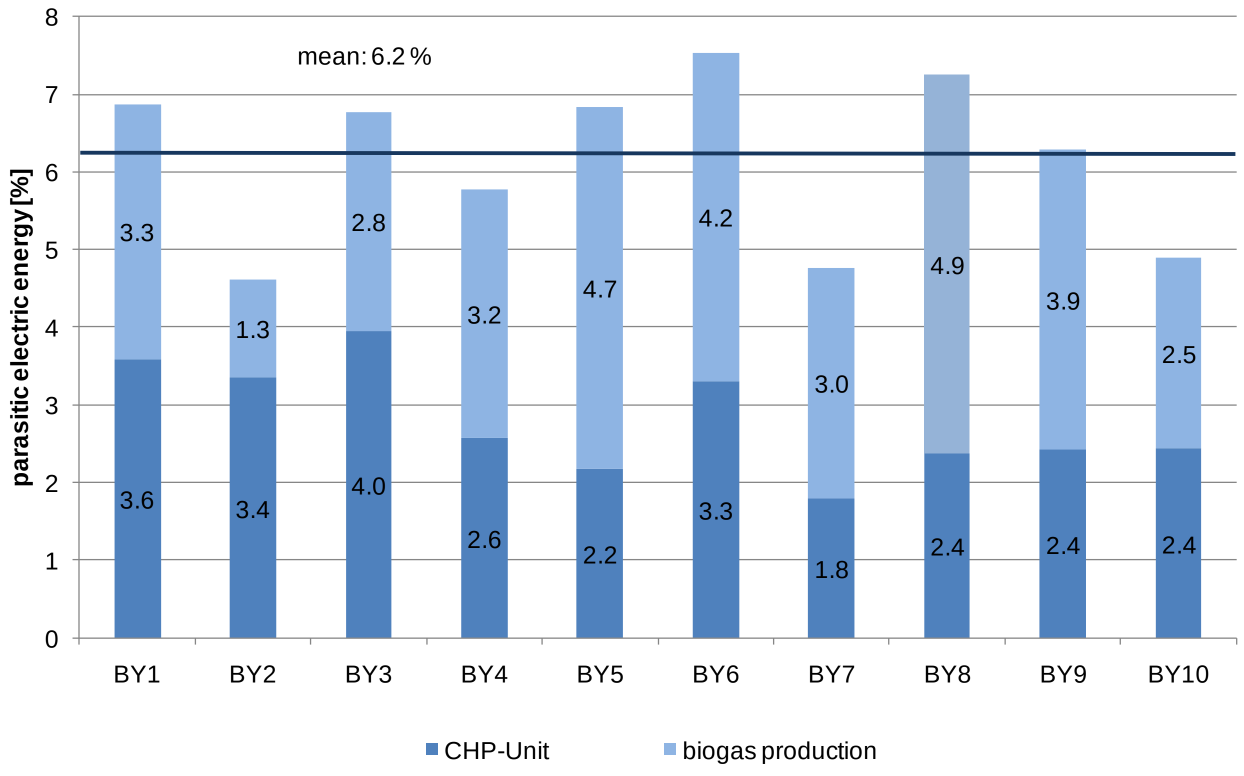


Figure 4.41: Parasitic electric energy

4.7.1 Biogas Production

The electricity consumers to run the biogas production process and the proportion of the different electric consumers are shown in Figure 4.42.

As expected, agitators and feeding systems are the biggest electric consumers.

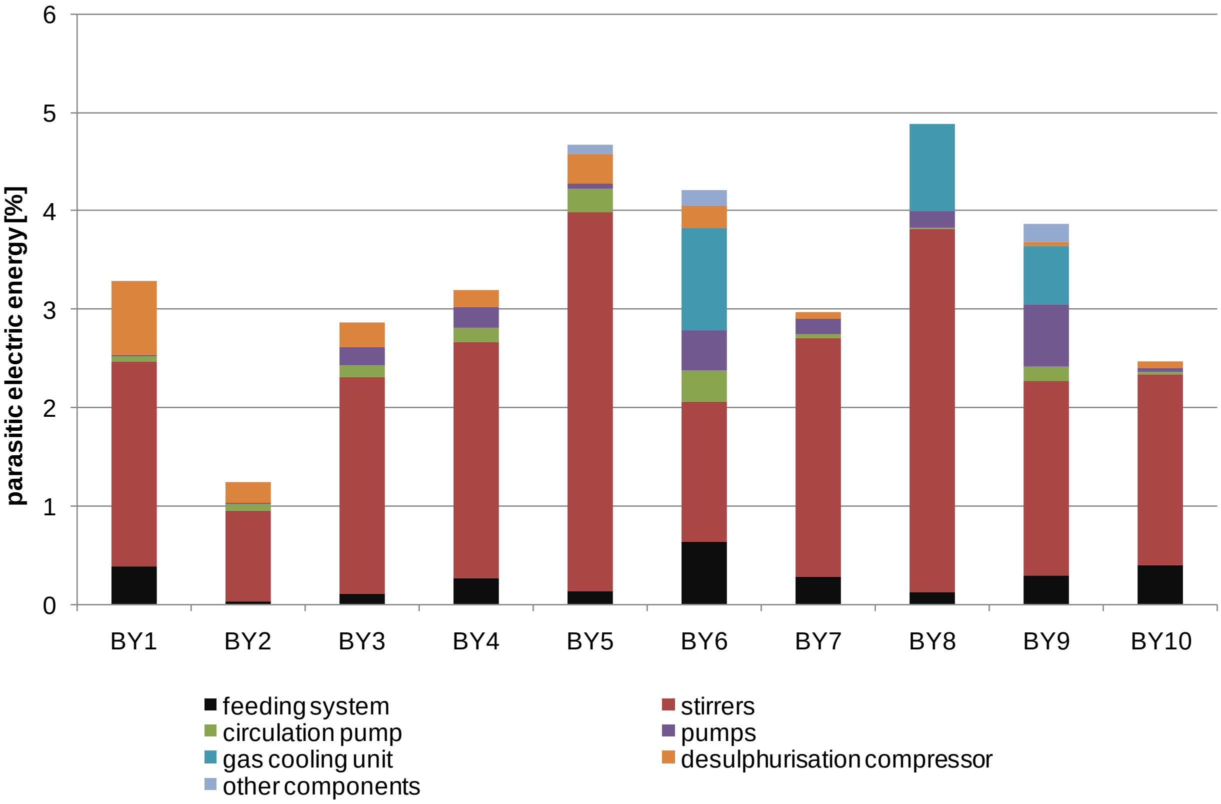


Figure 4.42: Biogas production parasitic electric energy and the proportion of different electric consumers

4.7.2 CHP-Unit

The CHP-Unit electric energy and the proportion of the different electric consumers are shown in Figure 4.43.

The biggest consumers of electric energy are emergency coolers, charge air coolers, and primary / secondary pumps.

4.7.3 Power Supply

The power supply of biogas plants can in principle be managed in three different ways: external supply from the grid, self supply and a combination of self and external supply.

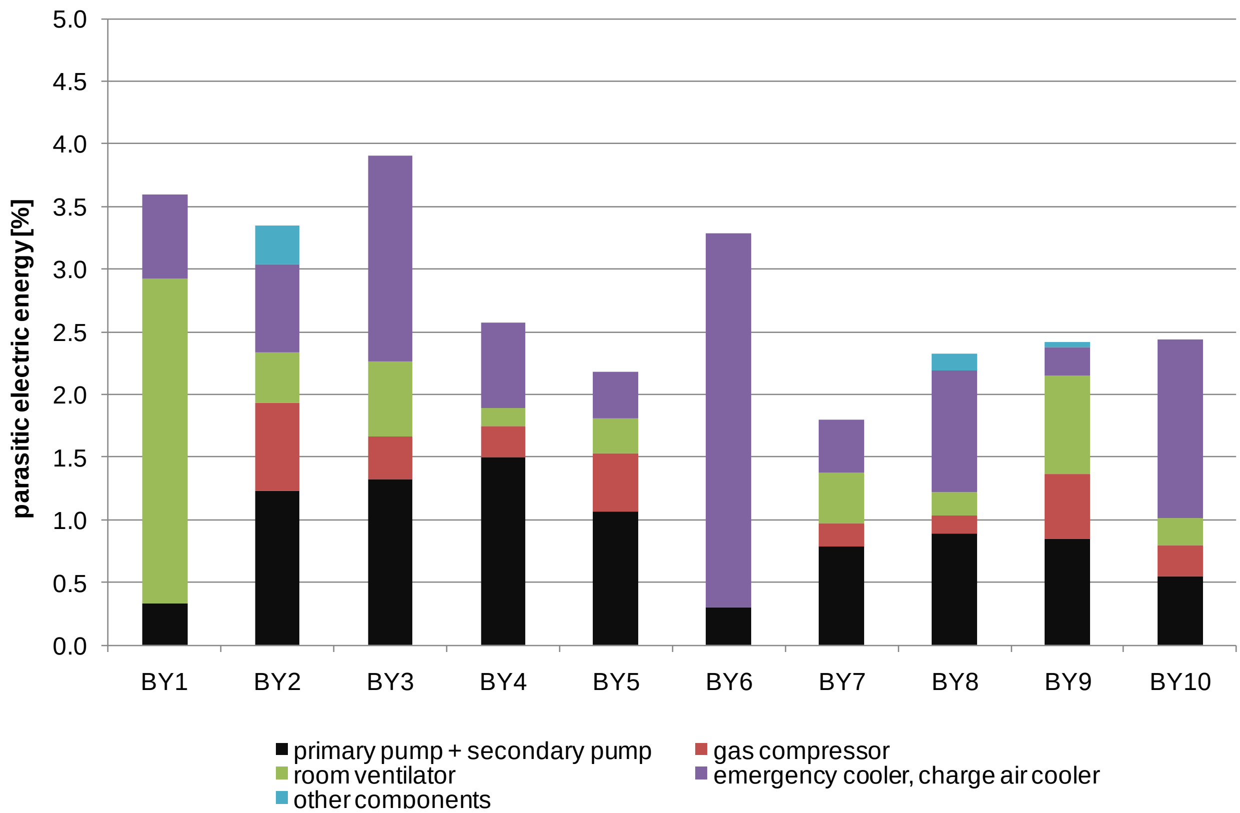


Figure 4.43: CHP-Unit parasitic electric energy and the proportion of different electric consumers

From both an ecological and economic point of view, an external supply is favourable. This type of power supply is beneficial, as more electric energy is fed into the electricity grid at a higher payment (feed-in payment for electricity is higher than the cost for electricity purchased from the grid) and electric energy is available even during CHP-Unit malfunction (biological process can be maintained during longer CHP-Unit malfunction).

Due to these advantages, it cannot be explained why only 4 biogas plants are externally supplied (Figure 4.44).

4.8 Methane Emissions

4.8.1 Biogas Leaks

The following section describes the detected biogas leaks, which are analysed according to Chapter 3.3.4.

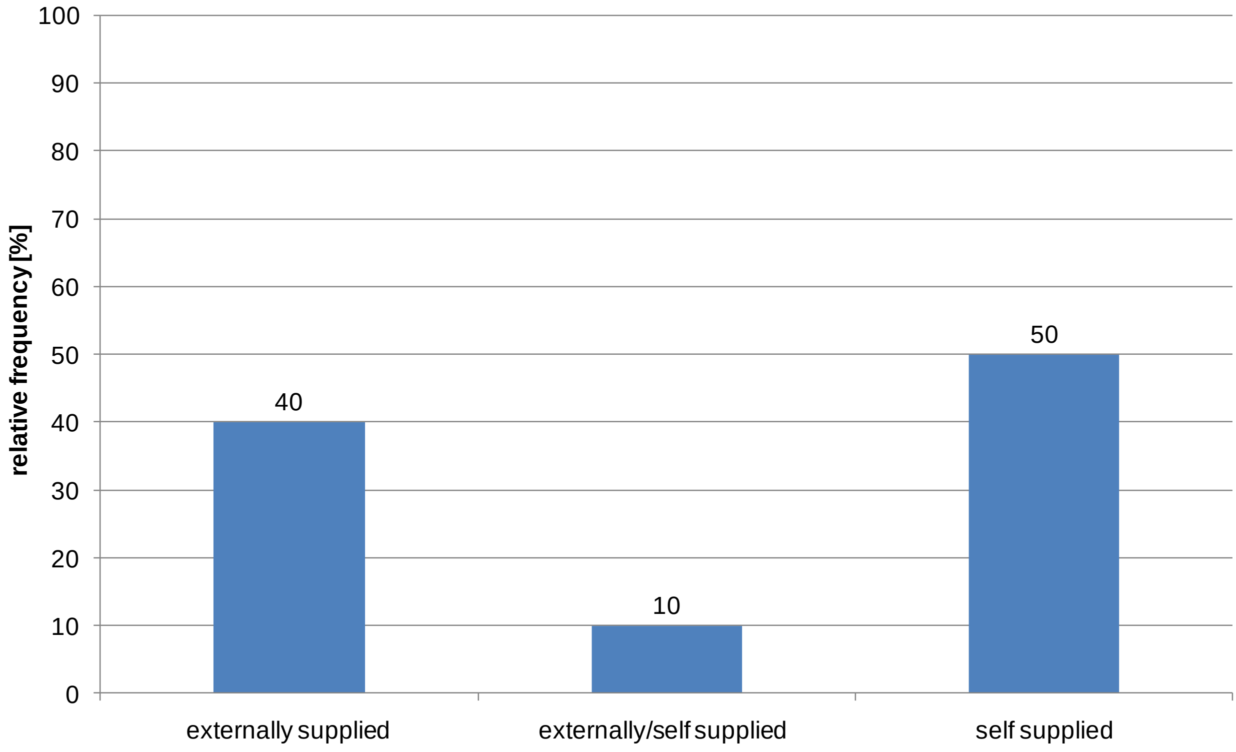


Figure 4.44: Type for power supply of the investigated biogas plants

4.8.1.1 Storage of Slurry

Before slurry is fed into the digester, it is kept in pre-storage tanks or in tanks beneath the slatted floor. Especially on summer days, the fermentation process starts already outside the digester causing methane emissions (category: design).

4.8.1.2 Feeding System

In spite of the fact that the investigated biogas plants are equipped with different feeding systems, methane emissions are detected at almost all feeding systems, especially at screw-feeding systems which are located on top of digesters (concrete ceiling) (Figure 4.45). These methane emissions cannot be avoided by maintenance (category: design).

4.8.1.3 Digester

Methane emissions at open overflows, a kind of connection between digesters, are also identified (Figure 4.46).

Figure 4.45: Biogas leak at the screw-substrate transition point

Figure 4.46: Open overflow

Further biogas leaks are detected at stirrers. Wire rope grommets, responsible for adjusting submersible motor mixers, are detected as location of biogas leaks (Figure 4.47). The reason for these leaks is a deficiency in maintenance. However, maintenance can be avoided by changing the design of the wire rope grommets.

Emergency openings at concrete ceilings are often equipped with sealed covers (Figure 4.48). However, biogas leaks occur due to ageing of the sealing materials.

Incorrectly installed portholes are also identified as location of biogas leaks (Figure 4.49). Very high emissions are detected at flushing devices due to non-mounted backflow preventer valves.

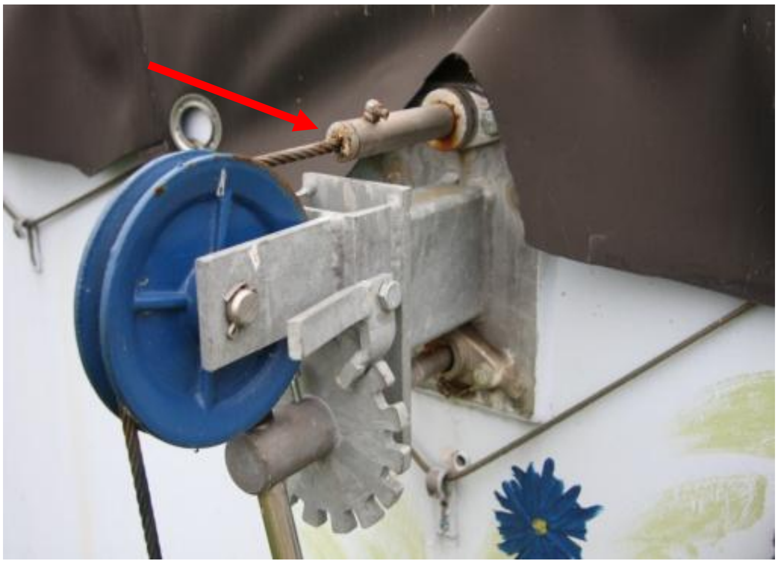


Figure 4.47: Wire rope grommet for a submersible motor mixer

Figure 4.48: Emergency opening

Figure 4.49: Incorrectly installed porthole

4.8.1.4 Biogas Storage

Gasholders are frequently detected as emission sources due to permeation of biogas through foil coverings (Bayerisches Landesamt für Umwelt 2009). The cause of these emissions is categorised as a design error, because permeation is unavoidable. However, leaks at gasholders are also categorised as deficiencies due to lack of maintenance and ageing (Figure 4.50).

Figure 4.50: Crack at a biogasholder (left) and in appropriately located biogasholder (right)

4.8.1.5 CHP-Unit

Mistakes in assembly and installation as well as deficiencies due to a lack of maintenance or ageing are indentified at CHP-Units. There, methane emissions are detected at connection elements (Figure 4.51).

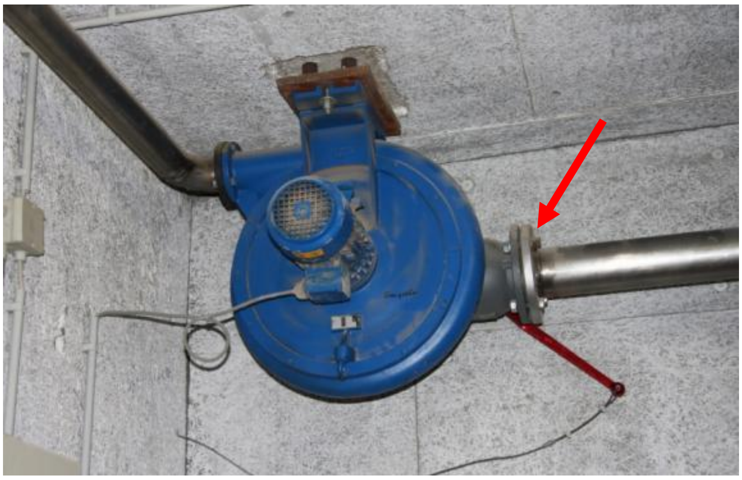


Figure 4.51: Biogas leak at a flange connection

4.8.2 Categorisation of Biogas Leaks

Figure 4.52 shows the identified biogas leaks of the investigated biogas plants including their categorisation.

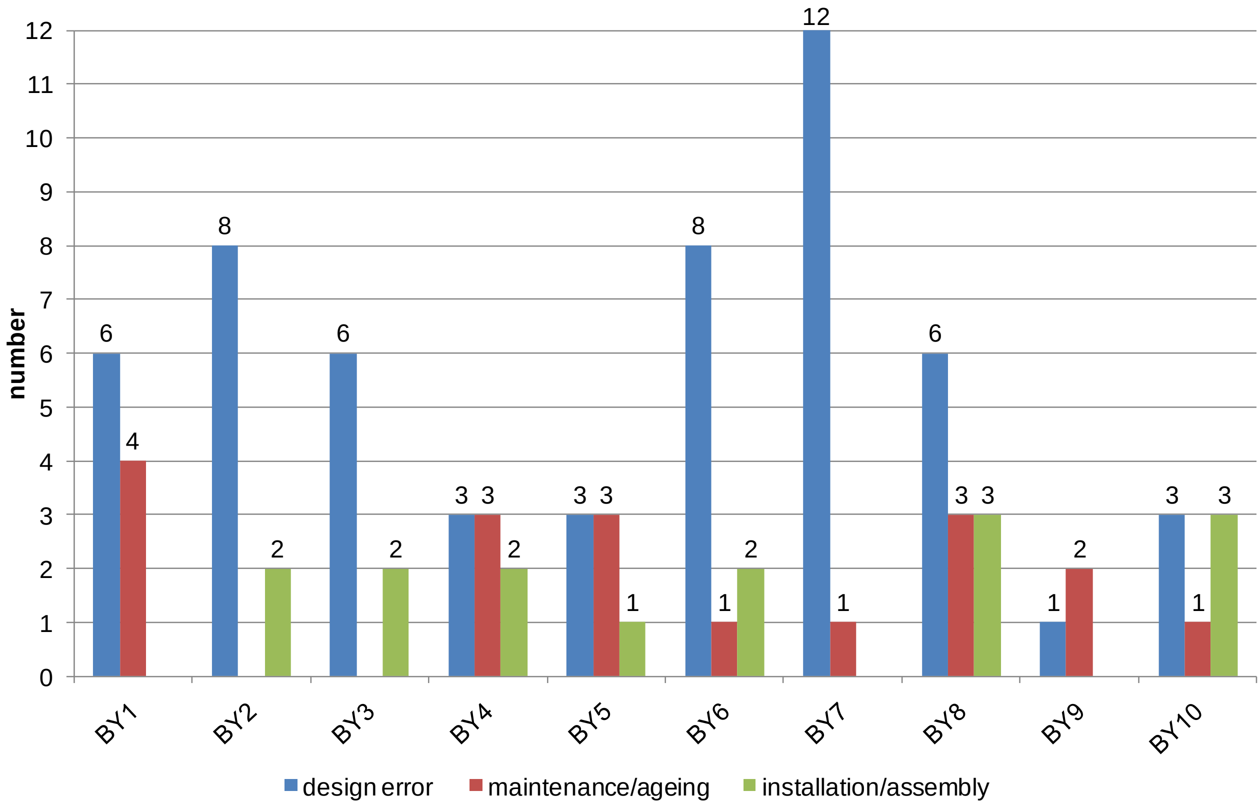


Figure 4.52: Identified and categorised biogas leaks

Most biogas leaks are detected at BY7. This high number can be attributed to the multiple usage of submersible motor mixers (4) with design errors (Figure 4.53).

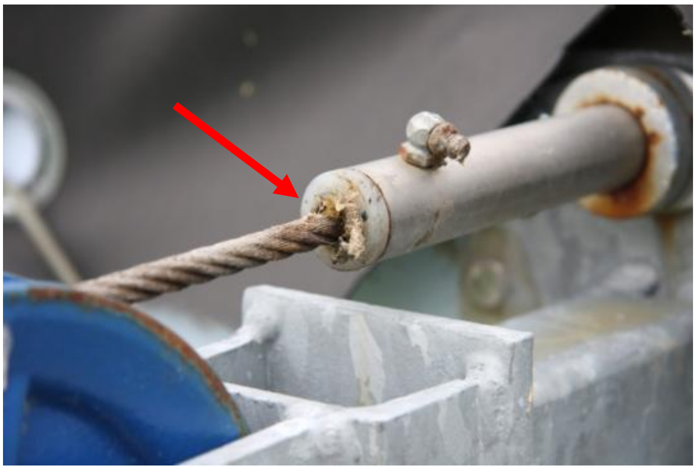


Figure 4.53: Wire rope grommet of a submersible motor mixer (BY7)

Additionally, emissions are detected at the feeding system, consisting of 2 feed screws (Figure 4.54).

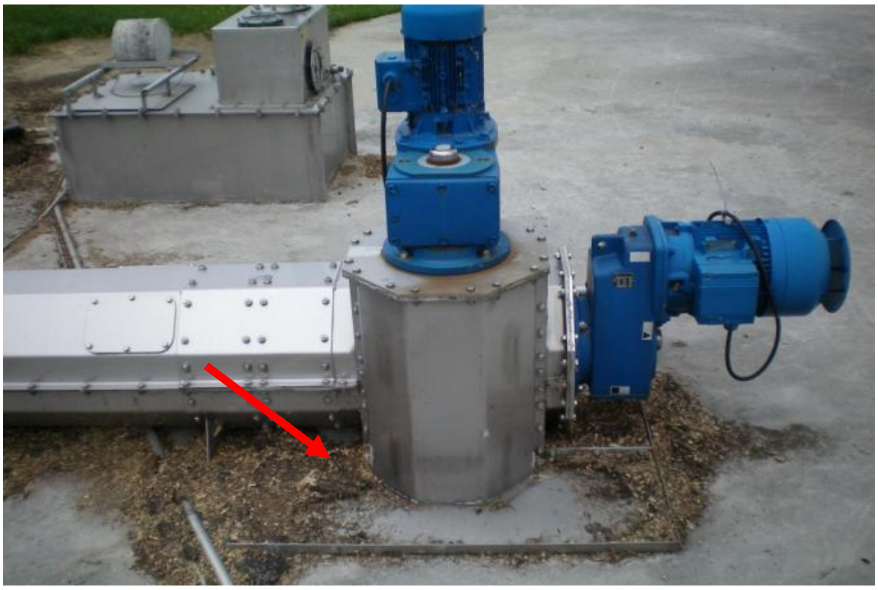


Figure 4.54: Screw-feeding system with methane emissions (BY7)

Furthermore, all tanks are connected to each other by means of open overflows (4) (Figure 4.55).

Figure 4.55: Open overflow (BY7)

Finally, a leakage at a gasholder and at an emergency opening are detected.

4.8.3 Quantification of Methane Emissions

The methane loss rate of the investigated biogas plants is determined according to the method described in Chapter 3.3.5.

Since the estimation of pressurised areas includes many parameters, the calculated amount of methane losses is just an estimate. Methane emissions at locations which are not directly connected with the digesters, such as pre-storage tanks or open overflows, are also considered.

When calculating the methane emissions for stored slurry, the methane yield from literature is used and losses caused by permeation of biogas through gasholders are taken into account. According to literature, the methane loss rate is 0.5 % (Vogt et al. 2008).

Figure 4.56 shows the methane losses in relation to the produced amount of methane.

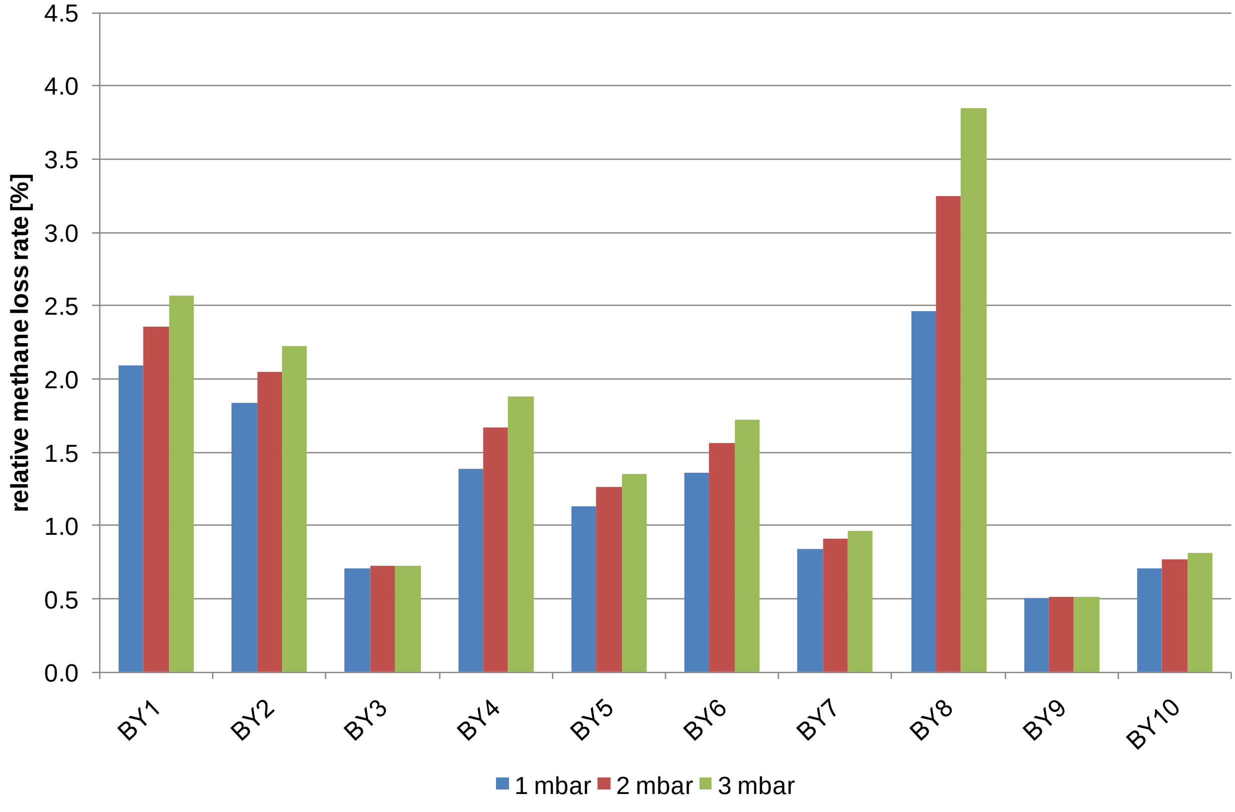


Figure 4.56: Calculated methane loss rate for a pressure range of 1 mbar - 3 mbar

The pressure of biogas within the digesters fluctuates, so the methane loss rate is calculated for a pressure range of 1 mbar and 3 mbar.

At a pressure of 1 mbar the mean relative methane loss rate is 1.3 %. The calculated mean methane loss rate at a pressure of 2 mbar is 1.5 %, and at a pressure of 3 mbar it is 1.7 %.

BY8 has a methane loss rate of 3.9 % at a pressure of 3 mbar. This is caused by long cracks and thus large areas of leakage. As mentioned before, the number of methane leaks does not indicate the amount of methane emissions; BY7 is a good example of this. At BY7, the highest number of biogas leaks is detected, but the calculated methane loss rate (0.96 %) is below the mean of the 10 investigated biogas plants.

As the relative methane loss rates vary over a wide range, there is potential for improvement.

4.8.4 Remaining Biogas Potential

The methane losses from non-gas-tight covered residue storage tanks are not measured on-site. In the climate gas balance sheets these emissions are considered by using values from literature. The number of biogas plants with gas-tight residue storage tanks is shown in Figure 4.57.

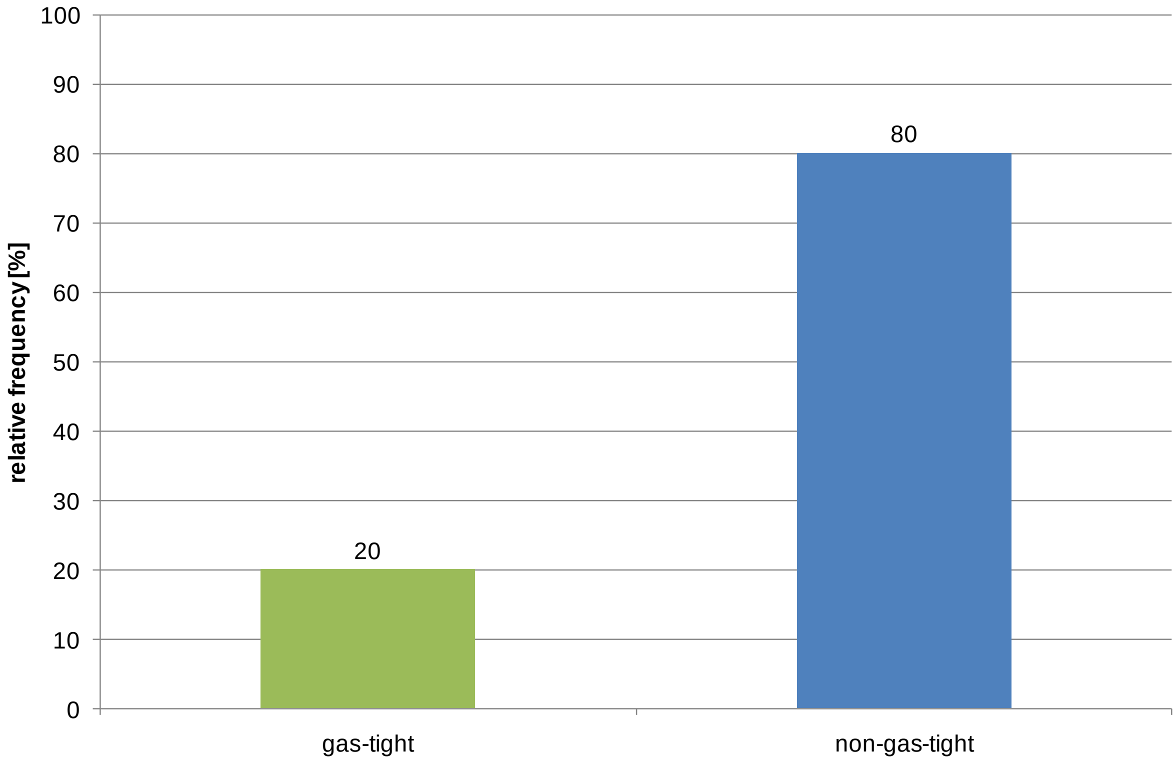


Figure 4.57: Relative frequency of gas-tight and non-gas-tight residue storage tanks

For the determination of the remaining biogas potential, substrate samples are taken from the overflows between the post-digester and non-gas-tight residue storage tank. In case of gas-tight residue storage tanks samples are taken from the residue storage tanks. During the sample collection period, BY1 had biochemical problems, thus, no sample was taken. The other plant without a sample is BY8, due to a very long hydraulic retention time and a gas-tight residue storage tank.

The remaining biogas potential (Figure 4.58) is determined via batch mode, which takes 40 days.

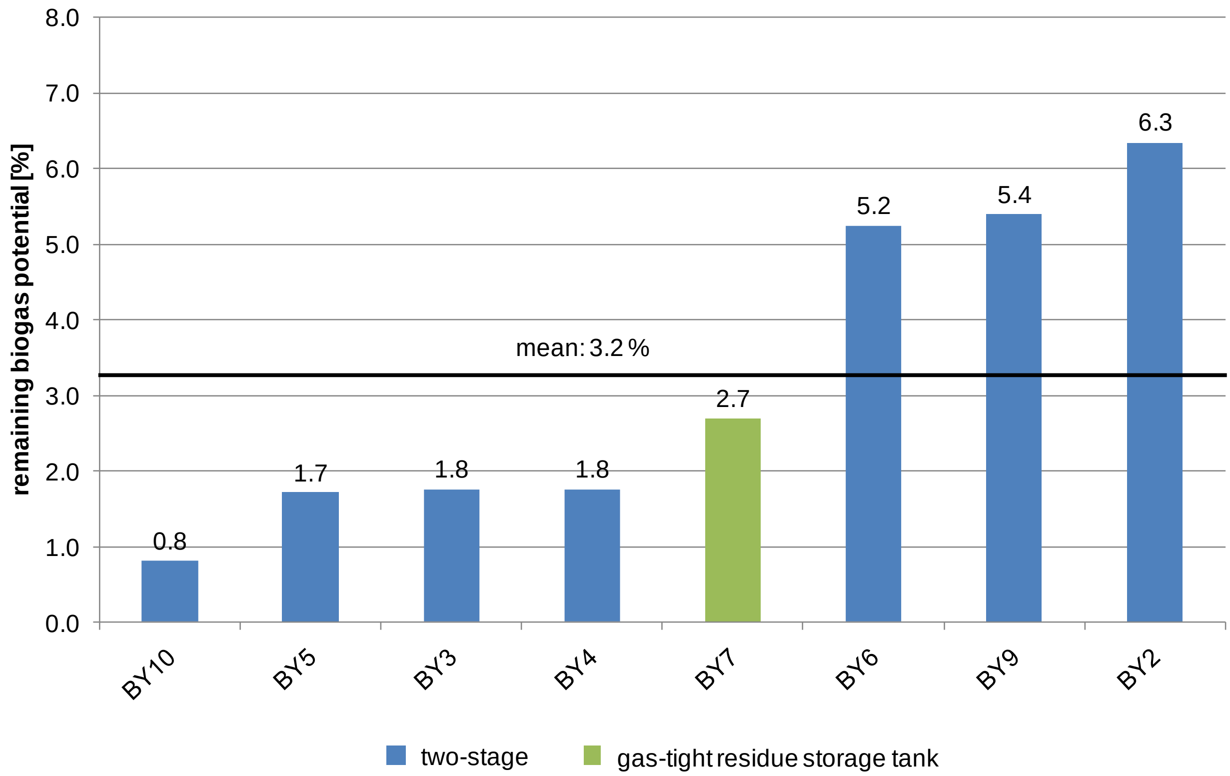


Figure 4.58: Remaining biogas potential of the investigated biogas plants

The relative remaining biogas potential is calculated by dividing the measured methane losses ($Nm^3/t_{digestate}$) by the produced methane volume flow. Therefore, the loss of mass caused by the biogas production process is considered. The relative remaining biogas potential gives an indication of the plant efficiency. High values indicate a bad substrate conversion efficiency, whereas low values show a good substrate conversion efficiency (Fachagentur Nachwachsende Rohstoffe 2009c).

BY2 has the highest remaining biogas potential (6.3 %), seven times that of BY10 (0.8 %). Most of the investigated biogas plants have a remaining biogas potential below the mean of 3.2 %. The low remaining biogas potential can be attributed to high specific digester volumes and thus longer hydraulic retention times (Chapter 4.3.1.1).

Figure 4.59 indicates the remaining biogas potential in comparison to the hydraulic retention time. As expected, there is quite a clear connection between hydraulic retention time and remaining biogas potential. Long hydraulic retention times result in low remaining biogas potential.

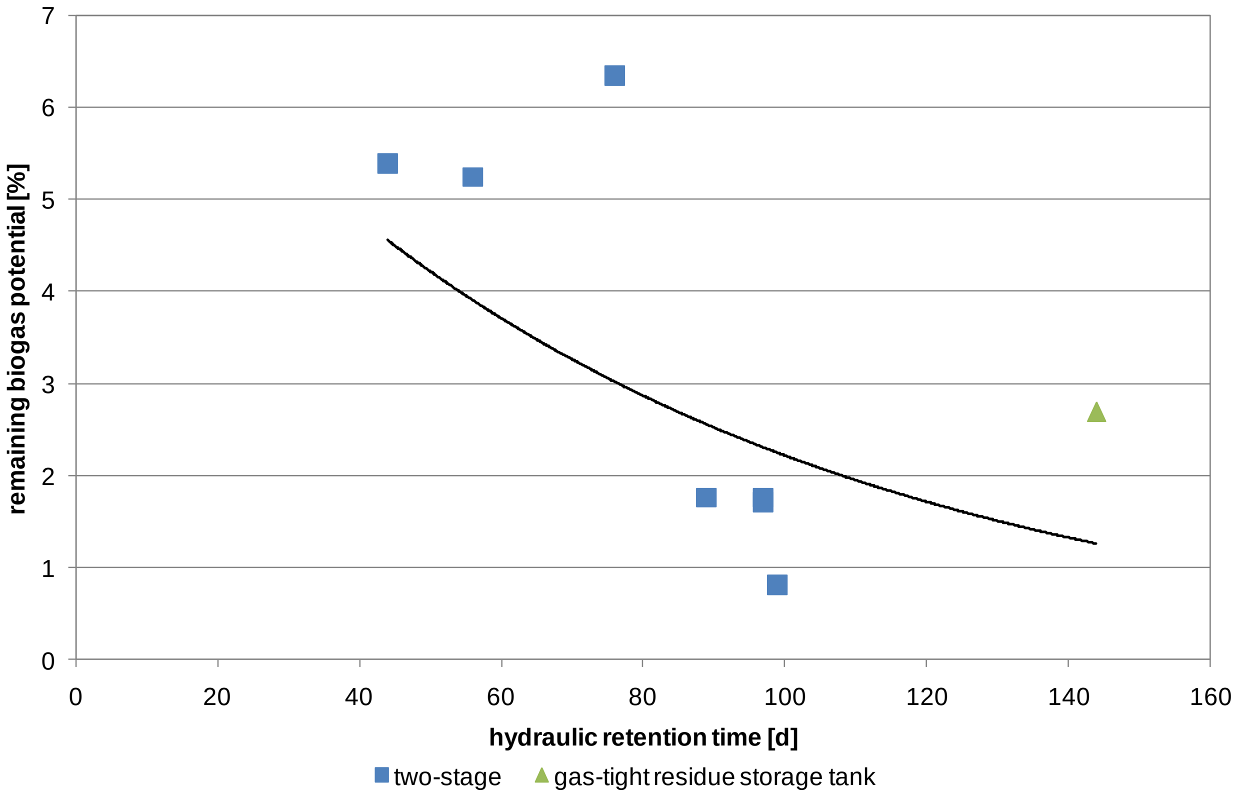


Figure 4.59: Remaining biogas potential in comparison to the hydraulic retention time

The relative remaining biogas potential in comparison to the volume load is shown in Figure 4.60.

As a result, the varying values of the remaining biogas potential indicate high optimisation possibilities.

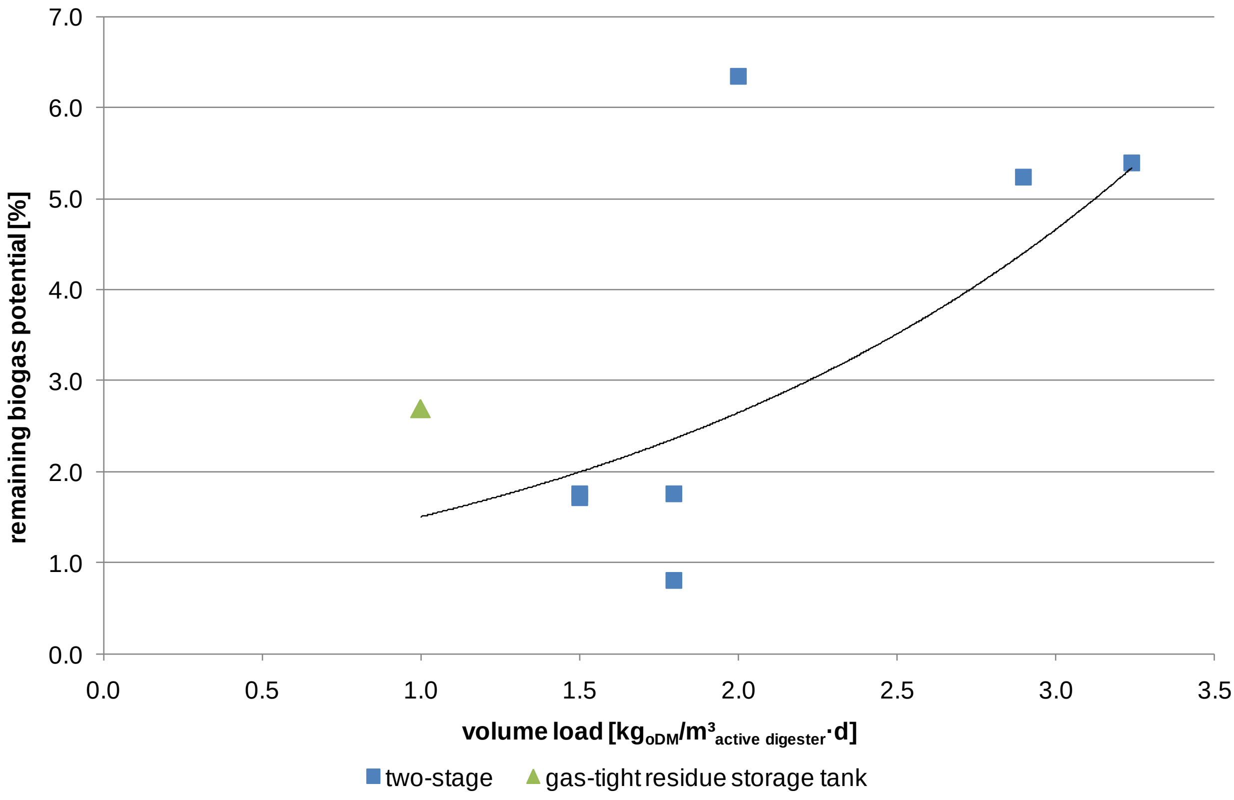


Figure 4.60: Remaining biogas potential in comparison to the volume load

4.9 Greenhouse Gas Balance

The results of the greenhouse gas analysis are discussed in this chapter. The main input variables for the balances are the data from measurements regarding the parasitic electric energy and the quantification of methane emissions. Further methane emissions, such as exhaust gas from the CHP-Units and diffuse emissions from foil coverings, are taken from standard literature. The emissions due to the remaining biogas potential in the residue storage tank are also considered using standard values. Samples had been taken for the determination of the remaining biogas potential, but these samples are not representative. The measured remaining biogas potential is expected to be higher than that occurring in non-heated residue storage tanks. Thus, the measured data is disregarded and instead standard values (2.5 % of the produced amount of methane) are used for the greenhouse balance sheets.

Positive factors regarding the greenhouse gas balance are the credits for producing electricity and heat (cogeneration bonus). Another credit is attributed for using slurry/manure as feedstock for the biogas plant.

Figure 4.61 shows the results regarding loads and credits subdivided into sections. Loads which contribute to emissions are displayed above the horizontal axis, whereas credits for saving emissions are plotted below the horizontal axis.

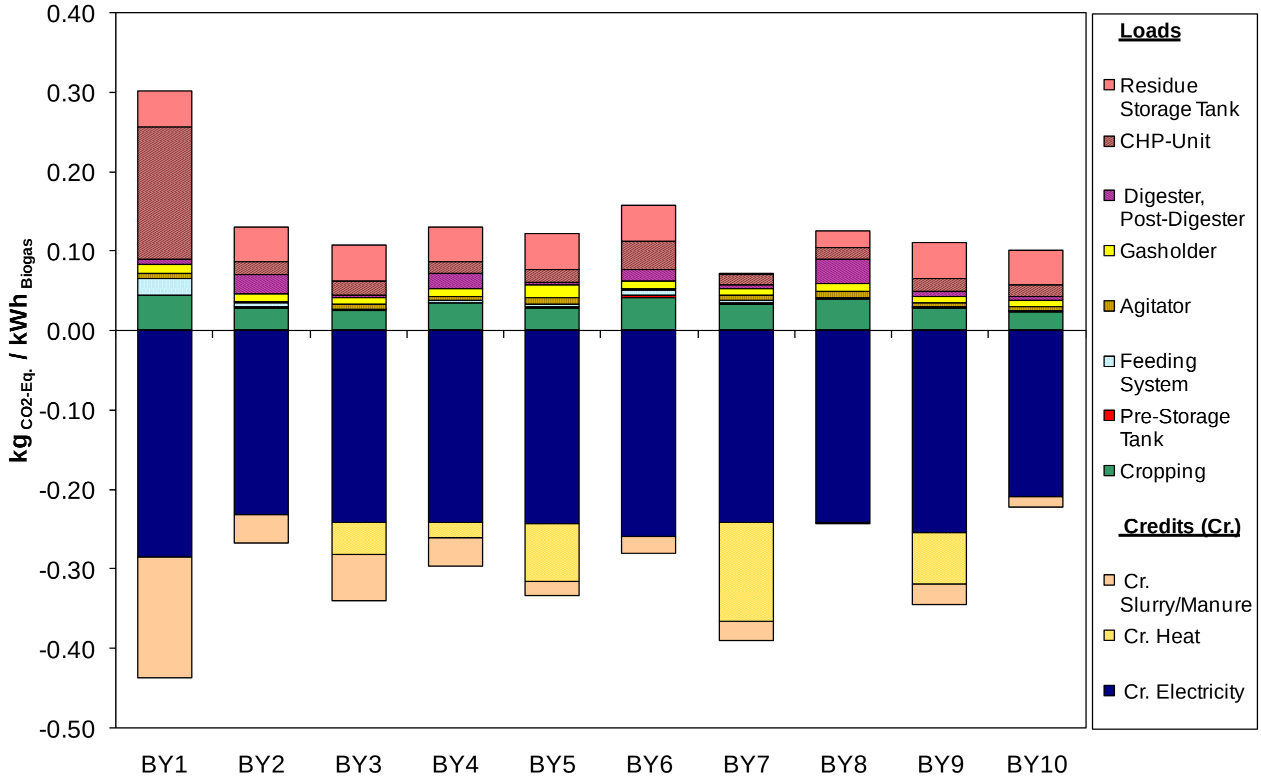


Figure 4.61: Greenhouse gas balances of the investigated biogas plants

Credits for the production of electricity and heat have a positive effect on the climate protection, as shown at all 10 biogas plants, however there is still potential for optimisation.

The first factor to consider is the amount of electricity produced. It can be increased through the use of highly efficient CHP-Units and/or an optimised biogas plant operation, which ensures optimised substrate conversion efficiency. It is very important to maintain a high overall CHP-Unit efficiency. This can be achieved by utilising heat to a larger extent. However, this is a big challenge due to the frequently limited availability of heat consumers near biogas plants. Furthermore, the usage of slurry/manure as feedstock for biogas plants also contributes to the reduction of greenhouse gases, due to the reduction of emissions of methane, which would normally occur while storing the slurry/manure in non-covered tanks.

There is also potential for optimisation regarding the loads within the greenhouse gas balances. It is found that methane emissions can be reduced by avoiding non-covered residue storage tanks and diffuse sources of methane. The provision of renewable raw materials is also a source of greenhouse gas emissions, however, these loads can be reduced by utilising organic waste as feedstock, and an optimised substrate conversion efficiency can contribute to a reduction of loads.

4.10 Economy

The return on assets (ROA) is calculated according to the method described in Chapter 3.3.7. Figure 4.62 shows the ROA of the investigated biogas plants for the years 2008 and 2009.

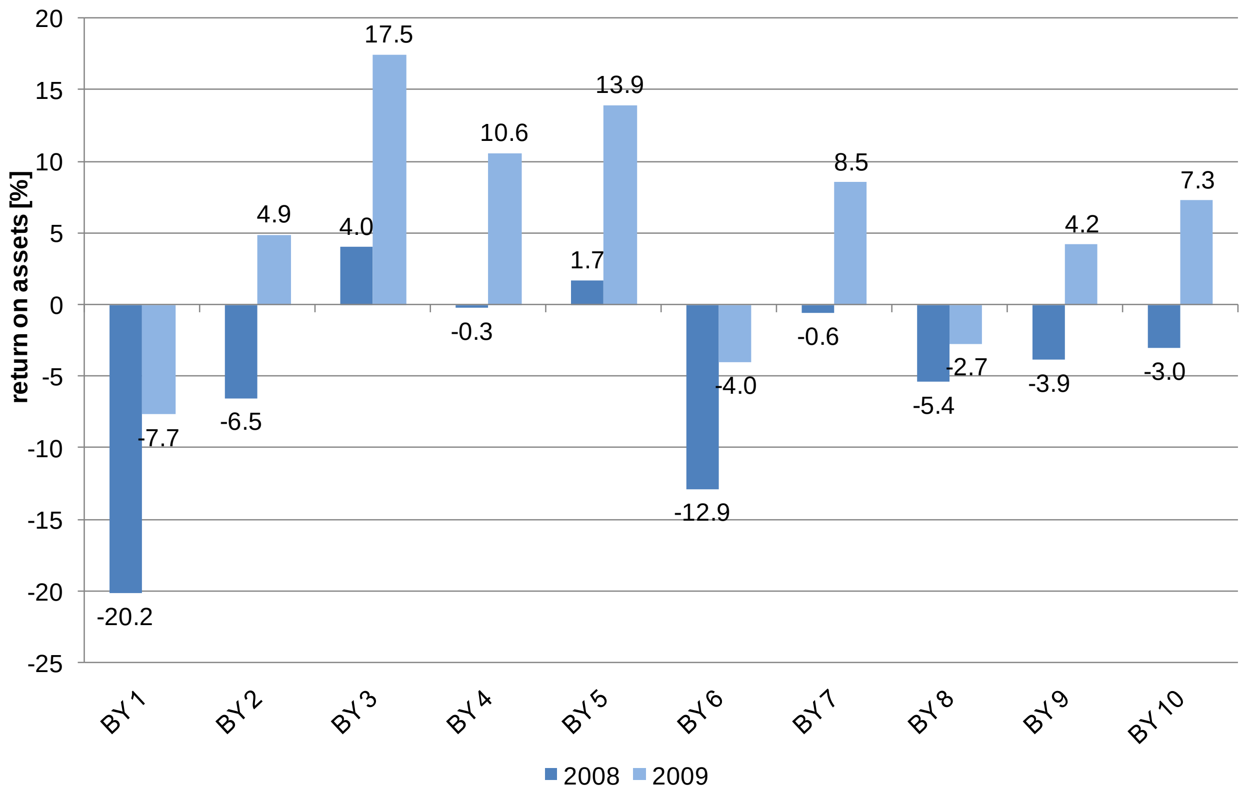


Figure 4.62: Return on assets of the investigated biogas plants

Taking a closer look at the 10 biogas plants, it is found that the ROA varies dramatically. In 2008, the current expenses of some biogas plants are higher than the income.

The amendment to the EEG in 2009 led to the improvement of the economic situation of all biogas plants (Figure 4.62, year 2009). These improvements can be attributed to the introduction of compensations, such as the initiation of the slurry bonus and the clean air bonus, and the higher payments for using renewable raw materials (RRM).

The intention of the EEG 2009 to subsidise smaller biogas plants has also been achieved, as Figure 4.62 shows.

BY1 receives no cogeneration bonus and has a low CHP-Unit usage rate. Furthermore, a large amount of ignition oil is consumed. These preconditions are the cause of the negative ROA in 2008 and 2009.

The increased payments from the EEG 2009 have a considerable effect on the economic efficiency of BY2 and lead to a positive return on assets in 2009. The bonus for slurry also contributes to the improved economic situation. Utilisation of heat according to the EEG requirements is not met.

BY3 uses heat to a greater extent. Thus, BY3 receives the cogeneration bonus in addition to the bonus for using slurry. However, heat is not sold to external consumers. The cost for feedstock is low due to a high proportion of livestock slurry. These preconditions result in a highly profitable biogas plant.

In the year 2008, the biogas plants BY4 and BY5 have a marginal economic efficiency. In 2009 the higher payments of the EEG 2009 have a significant effect on the economic efficiency of both plants. This leads to reasonable profitability because of a moderate heat utilisation (cogeneration bonus) and the usage of slurry (slurry bonus).

The economic situation of BY6 is poor for both 2008 and 2009. The reasons for this are expenses for ignition oil, lack of a cogeneration bonus and a low CHP-Unit usage rate caused by deficiencies in maintenance and management. However, the bonus for the usage of slurry is obtained.

BY7 uses all of its produced heat (cogeneration bonus). Based on this precondition, and the higher payments of the EEG 2009, the return on assets is reasonable.

Biogas plant BY8, which does not use any slurry, has a negative return on assets in 2008 as well as in 2009. The main reasons for this are the lack of heat utilisation and slurry bonus.

The economic situation and the compensations paid for BY9 and BY10 are similar. Both plants have a negative return on assets in 2008 and are profitable in 2009. Both plants receive the basis compensation, the renewable raw material bonus, the slurry bonus and the clean air bonus. The only difference is found in the means of heat utilisation. BY9 uses the produced heat moderately. Due to this, BY9 receives the cogeneration bonus. In contrast, BY10 does not use heat according to the EEG requirements, hence, does not receive the cogeneration bonus.

5 Development of Optimisation Concepts

Based on the analysis of the current situation, a benchmark is carried out according to the following criteria:

- economic potential for optimisation,
- ecological potential for optimisation,
- potential for realisation.

This evaluation finally leads to the development of optimisation concepts with tangible suggestions for improvements.

The rating is carried out according to the classification and allocation of points as shown in Table 5.1. Topics which are rated at 6...9 points are promising targets, with a high potential for improvement. The result of the evaluation matrix is shown in Table 5.2.

Table 5.1: Evaluation criteria

	Rating		
	low	medium	high
Economic Potential for Optimisation	low additional income	medium additional income	high additional income
Ecological Potential for Optimisation	low reduction of emissions	medium reduction of emissions	high reduction of emissions
Potential for Realisation	implemented in most plants	implemented in many plants	rarely implemented in plants
Points	1	2	3
Overall Score	3	4-5	6-9

Economic Potential for Optimisation

The economic potential for optimisation is rated according to additional income or savings in comparison to the necessary expenses.

Ecological Potential for Optimisation

The ecological potential for optimisation is rated based on the amount of avoided greenhouse gas emissions in comparison to the necessary expenses.

Potential for Realisation

The rating of the potential for realisation considers factors such as the demand of optimisation within the investigated biogas plants, the technical feasibility and the transferability to other biogas plants.

Table 5.2: Evaluation with regard to the potential for optimisation

Areas of Investigation	Economic Potential for Optimisation	Ecological Potential for Optimisation	Potential for Realisation	Overall Score
Substrate Supply				
Distance to Farmland	low	low	low	3
Required Farmland	low	low	low	3
Substrate-Origin: Owned or Purchased	low	low	low	3
Loading of Substrate				
Distance Silo - Feeding System	high	low	medium	6
Time for Loading the Feeding System	high	low	medium	6
Biogas Production				
Fermentation Process	high	low	medium	6
Used Substrates	low	medium	low	4
Biology	low	low	medium	4
Gas Processing				
Desulphurisation Efficiency	medium	low	medium	5
Dehumidification Efficiency	medium	low	medium	5
Biogas Utilisation				
CHP-Unit	high	high	high	9
Heat Utilisation	high	high	high	9
Measurement and Control Technology				
Measurement	medium	medium	medium	6
Documentation	medium	low	medium	5
CHP-Unit Usage Rate	high	medium	medium	7
Parasitic Electric Energy				
Total Parasitic Electric Energy	high	medium	medium	7
Feeding System	high	low	low	5
Stirring	high	low	medium	6
Pump	medium	low	medium	5
Desulphurisation	high	low	high	7
Dehumidification	high	low	medium	6
Power Supply	high	low	medium	6
Methane Emissions				
Biogas Leaks	medium	high	high	8
Remaining Biogas Potential	high	high	medium	8

Based on the evaluation matrix, the following 8 approaches are elaborated to improve the plants` ecology and economy:

1. Shortening of the distance between silo and feeding system
2. Improving substrate conversion by using highly efficient CHP-Units
3. Improving substrate conversion by avoiding biogas leaks
4. Reducing methane emissions and improving substrate conversion by covering residue storage tanks
5. Lowering desulphurisation electric energy consumption via air injection
6. Improving heat utilisation via structured planning approach
7. Improving heat utilisation by implementing heat meters
8. Improving utilisation of the CHP-Unit

Besides these 8 approaches other topics are also rated from 6…9 points. However these topics are not considered in detail due to the following reasons:

- plant-specific approaches without transferability (fermentation process, stirring system),
- no availability of precise information/data for the evaluation of the ecological and economic potential (gasholder, feeding system electric energy consumption, de-humidification),
- only economic potential without ecological aspects (power supply).

5.1 Shortening of the Distance between Silo and Feeding System

The loading time for the feeding system is a result of the distance from silo to feeding system, the used handling system (shovel capacity), the required number of trips per day and the driveway quality.

Another important factor to consider is the storage capacity of the feeding system. It has to be able to store the daily added feedstock.

Figure 4.4 (see page 60) shows the diverse distances between silo and feeding system.

Large distances from silo to feeding system create increased costs. To show this, two investigated biogas plants are compared with each other. Both biogas plants have an electric capacity of 380 kW_{el} and use the same handling system (telescopic handler).

Table 5.3 shows the expenditures of both biogas plants regarding the distances between silo and feeding system. The cost for working hours is assumed to be 15 €/h, the fuel cost is considered to be 0.55 €/l (Döhler et al. 2009b). The calculation of greenhouse gas emissions is carried out according to the JEC E3-database (version 37-7-2008).

Table 5.3: Expenditures of two biogas plants regarding the distance from silo to feeding system

Biogas Plant	**Distance Silo – Feeding System**	**Trips per Day**	**Total expenditure of Time**	**Fuel consumption**	**Cost per Loading**	**Cost per Year**	**GHG emissions**
	[m]		**[h/d]**	**[l_{Diesel}/h]**	**[€]**	**[€/a]**	**[$kg_{CO2-Eq.}$/a]**
A	80	10	0.5	5	0.89	3,240	2,868
B	240	17	2.5	5	2.61	16,200	14,339

Biogas plant A has expenditures (work and fuel) of 3,240 €/a for loading the feeding system, whereas costs of 16,200 €/a at biogas plant B are incurred. A reduction in fuel consumption also contributes to the reduction of GHG emissions. A comparison of both plants shows that biogas plant A emits less CO_2 (11,471 $kg_{CO2\text{-}Eq.}$/a) than biogas plant B. This is equivalent to the emissions of a car driving about 64,000 km.

Biogas plant A is a good example of a well planned driveway between silo and feeding system. The mean distance is only 80 m, furthermore, it is tarred. This allows the handling system to operate at higher speed, resulting in daily time expenditure of only 30 minutes for the loading of the feeding system (Figure 4.6).

Biogas plant B has a higher expenditure of time due to a longer transport distance (240 m), a bigger amount of added solid feedstock, a non-tarred driveway and an altitude difference (Figure 4.7).

Thus, considerable differences in cost and GHG emissions arise from the comparison of biogas plant A and B.

For the optimisation of driveways between silo and feeding system, it is recommended to locate silos close to the feeding system. As a result of this, the expenditure of time can be reduced, other disadvantages (GHG emissions) can be avoided.

For the economic evaluation of driveways, it has to be considered that already existing silos can be used for biogas plants. This can reduce investment costs. Silos must be placed in a way that the layout of biogas plants is not compromised.

5.2 Improving Substrate Conversion by using Highly Efficient CHP-Units

The new acquisition of CHP-Units with a high electrical efficiency is a good opportunity for the economic optimisation of biogas plants. For biogas plants with a low heat utilisation and old CHP-Units this is especially worth considering.

The actual electrical efficiency of CHP-Units can sometimes differ from measurements at test-benches. Thus, it is recommended to seek out practical experience before selecting the CHP-Unit. Furthermore, highly efficient circulation pumps are recommended to be used as this can reduce the CHP-Unit electric energy consumption.

A better electrical efficiency of a new CHP-Unit has several advantages. A lower amount of feedstock and biogas are needed for the production of the same amount of electric energy, furthermore, less farmland is required. In contrast to this, CHP-Units with a high electrical efficiency have an increased acquisition cost. However, these higher investments can have a short payback period.

In some cases, due to insufficient range of products on offer, higher electrical efficiency of CHP-Units can only be achieved by increasing the electric capacity of the CHP-Units. If this is the case, additional costs for grid integration and approval need to be clarified.

The positive effects of increased electrical efficiency can be seen by comparing two CHP-Units.

The old CHP-Unit has a capacity of 190 kW_{el} and an electrical efficiency of 38.5 %. This CHP-Unit is compared with a CHP-Unit with a capacity of 220 kW_{el} and an electrical efficiency of 40.6 % (Table 5.4).

The additional investment for a CHP-Unit of 220 kW_{el} is € 55,000, however, much more electric energy can be produced as a result of the increased electric capacity (Table 5.4). As a result of the higher electric capacity, the required feedstock (maize yield assumed:

50 t/ha) increases, but only by 350 t/a. Due to the changes, the hydraulic retention time is shortened from 97 to 61 days, and the volume load rises from 1.5 $kg_{oDM}/m^3_{active\ digester} \cdot d$ to 1.7 $kg_{oDM}/m^3_{active\ digester} \cdot d$.

Table 5.4: Effects of using highly efficient CHP-Units

CHP-Unit			**Old**	**Modern**
Electrical efficiency		[%]	38.5	40.6
Electric capacity		[kW_{el}]	190	220
Effects	Electricity Output	[kWh_{el}/a]	-	+ 233,000
	Required Substrate (maize silage)	[t/a]	-	+ 350
	Required Farmland	[ha]	-	+ 7
	Revenue	[€/a]	-	+ 29,000
GHG emissions		[$kg_{CO2\text{-}Eq.}$/a]	-	- 134,309

Considering the increased investment and use of feedstock, a payback period of only 2 years can be achieved. Moreover, an additional income of € 225,000 can be obtained over a period of seven years, the normal lifetime of a CHP-Unit. Taking the additional investment of € 55,000 into account, earnings of € 165,000 are likely to be achieved.

Besides the increased electricity production, a reduction in GHG emissions of about 134 $t_{CO2\text{-}Eq.}$/a can also be realised. This is equivalent to the emissions of 12 persons per year.

A comparison of a further biogas plant is carried out. Therefore, two different CHP-Unit-combinations, each with a total electric capacity of 560 kW_{el} are compared (Table 5.5). Type 1 is a combination of three CHP-Units (each 190 kW_{el}, derated) with an electrical efficiency of 38.5 %. Type 2 is a combination of two CHP-Units (400 kW_{el} and 190 kW_{el}, derated) with an overall electric efficiency of 39.6 %.

The additional investment for type 2 is about € 25,000, but the feedstock requirement (maize yield: 50 t/a) can be reduced by about 274 t/a. The saving of feedstock is equivalent to a cost-saving of about 9,500 €/a (assuming a cost of 35 €/t for maize silage), and the demand of farmland for feedstock can be reduced by about 6 ha. This extends the hydraulic retention time from 99 to 114 days. In addition, the volume load is reduced from 1.8 $kg_{oDM}/m^3_{active\ digester} \cdot d$ to 1.5 $kg_{oDM}/m^3_{active\ digester} \cdot d$.

Table 5.5: Effects of using different combinations of CHP-Units

CHP-Unit			Type 1	Type 2
Electrical efficiency		[%]	38.5	39.6
Electric capacity		[kW_{el}]	560	
Effects	Electricity Output	[kWh_{el}/a]	4,828,105	
	Required Substrate (maize silage)	[t/a]	-	- 274
	Required Farmland	[ha]	-	- 6
	Revenue	[€/a]	-	+ 9,500
GHG emissions		[$kg_{CO2-Eq.}$/a]	-	- 9,774

Considering the increased investment and reduction in feedstock, a payback period of only about 2.5 years is achievable, and additional earnings of about € 47,000 can be expected over a period of seven years (Figure 5.1). Due to reduced feedstock requirements, the dependency on the market is diminished, thus, the economic situation of the biogas plant is improved. A reduction of GHG emissions of about 10,000 $kg_{CO2-Eq.}$/a can also be achieved, which is equivalent to that of a car driving about 54,300 km.

5.3 Improving Substrate Conversion by Avoiding Biogas Leaks

Emissions of methane are unnecessary losses that can be identified and avoided quite easily. In most cases, this can be done by the biogas plant operator himself.

As a precondition, a leakage detector, designed to detect methane, must be available. The investment for a leakage detector (explosion-proof) is about € 400...600. There is also the possibility of sharing a leakage detector among a number of plants to reduce the cost per biogas plant.

Biogas plants must be inspected for biogas leaks once a month. A higher frequency of inspections is recommended if plant modifications are carried out or leaks are assumed or notable (e.g. odour of biogas).

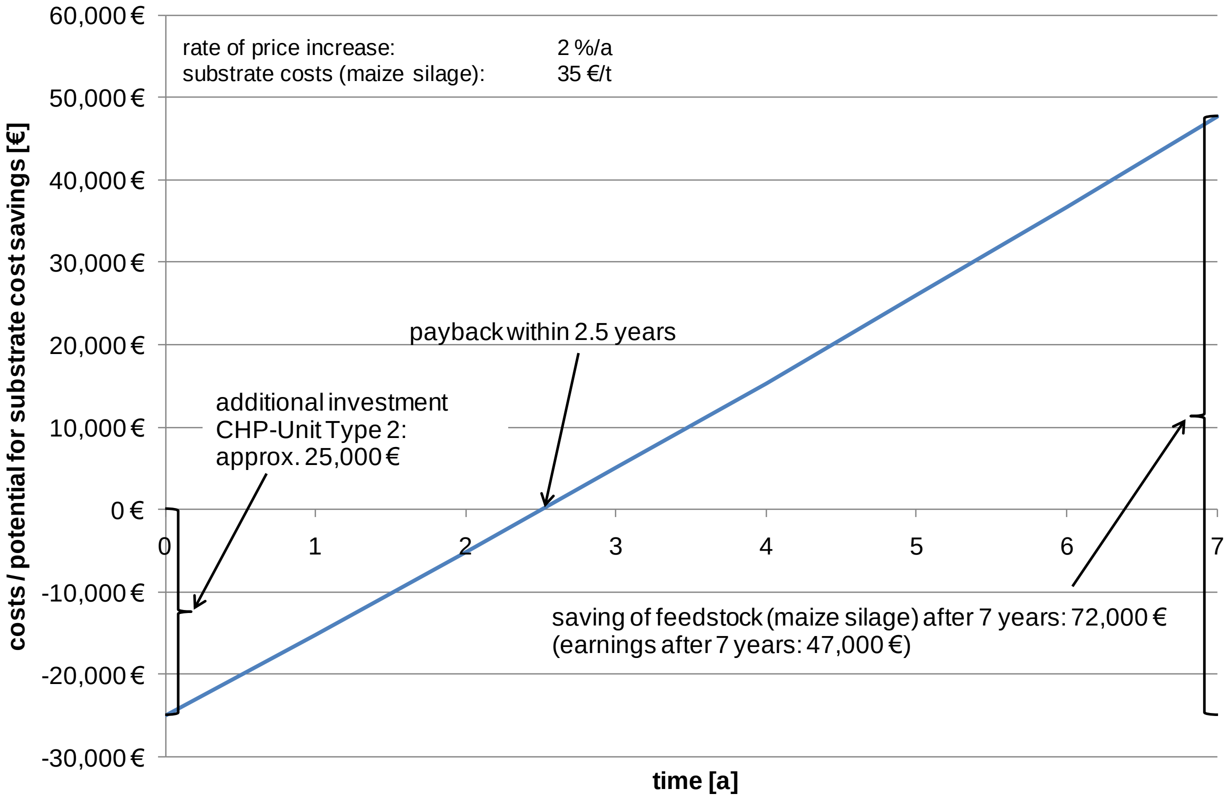


Figure 5.1: Effects of using different combinations of CHP-Units

Under different operational conditions, such as a changing pressure inside the digester, different biogas leakage rates occur. Thus, inspections with a leakage detector have to be carried out at different operating conditions of the biogas plant.

Table 5.6 shows common areas for biogas leaks and the corresponding recommended action to be taken.

The identified biogas leaks are divided into 3 categories: methane emissions caused by design errors, deficiencies due to a lack of maintenance or ageing and mistakes in assembly or installation.

Biogas leaks caused by mistakes in assembly and installation (e.g. incorrectly installed portholes or flange connections) as well as deficiencies due to a lack of maintenance or ageing (e.g. worn seals), can be easily fixed and do not incur high costs.

It is important to note that the detection of biogas leaks is carried out in a potentially explosive atmosphere. Thus, precautions need to be taken, especially during maintenance and repairs.

Table 5.6: Frequently identified biogas leaks with corresponding recommended action

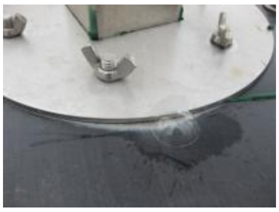
Biogas Leak		**Recommended Action**
Feeding Screw		Piston feeding system and/or feeding below substrate level
Open Overflow		Avoidance of open overflows in general
Wire Rope Grommet of a Submersible Motor Mixer		Re-grease the grommet after each movement of the wire
Mounting Agitator		Tighten the bolts; assemble according to manufacturers` recommendations (mistake in assembly)
Porthole		Fix gas backflow preventer valve and ball valve at intended place (mistake in assembly)
Gasholder		Seal according to manufacturers` recommendations
Flange Connection		Assemble according to manufacturers` recommendations (mistake in assembly: less screws)
Emergency Opening		Replace sealing

Figure 5.2 shows the savings in substrate costs (maize silage) per year. The recovery of 1 % of biogas with regard to the produced biogas has a high potential for reducing costs.

In the case of a 190 kW_{el} biogas plant, the following savings can be achieved:

- reduced substrate costs (maize silage): 1,400 €/a,
- reduced farmland usage (maize silage): 0.8 ha,
- saved substrate (maize silage): 41 t/a,
- avoided methane emissions: 4,161 m³/a,
- reduced greenhouse gas emissions due to the reduction in methane emissions and saved substrate: 75,917 $kg_{CO2\text{-}Eq}$/a (emissions of approx. 7 persons per year).

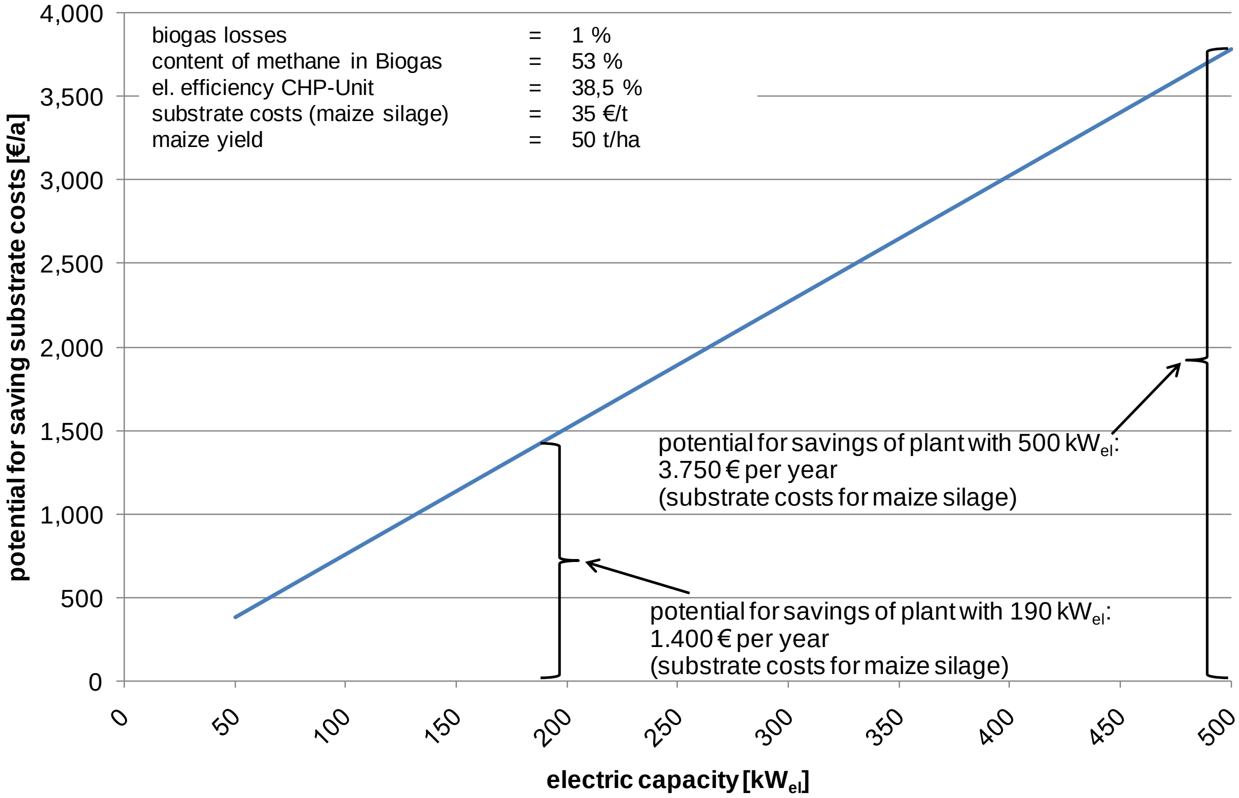


Figure 5.2: Potential for savings via reduction of biogas leaks

A 500 kW_{el} biogas plant can achieve the following savings:

- reduced substrate costs (maize silage): 3,750 €/a,
- reduced farmland usage (maize silage): 2.1 ha,
- saved substrate (maize silage): 108 t/a,
- avoided methane emissions: 10,950 m³/a,
- reduced greenhouse gas emissions due to the reduction of methane emissions and saved substrate: 199,785 $kg_{CO2\text{-}Eq.}$/a (emissions of approx. 17.5 persons per year).

Both examples prove that avoiding biogas leaks contributes significantly to the protection of climate and to a more profitable business.

5.4 Reducing Methane Emissions and Improving Substrate Conversion by Covering Residue Storage Tanks

The remaining biogas potential of the investigated biogas plants varies between 0.8 % and 6.3 %. This bandwidth can be traced back to factors such as different hydraulic retention times and substrates. A gas-tight-covering of residue storage tanks enables the energetic utilisation of the biogas from the residue storage tank and reduces methane emissions.

The remaining biogas potential is determined via batch mode, a test that takes 40 days at a temperature of 40°C. As non-covered residue storage tanks are not heated, the temperature of the digestate is assumed to be below 40°C. Thus, the remaining biogas potential can be assessed as the maximum potential.

Investment for gas-tight coverings

To realise a gas-tight tank covering, several steps have to be carried out. Besides the installation of a gas-tight foil, the inner surface of the tank must be coated, to prevent sulphuric acid corrosion. Existing agitators must be gas proof according to the guidelines for explosion protection. Additional measurement equipment (fill level of gasholder) and safety technology (underpressure/overpressure safety devices) also has to be installed.

The investment for a gas-tight covering for an existing concrete tank varies from € 60,000 (ø < 25 m) to € 85,000 (ø > 25 m).

Reduced methane emissions and feedstock requirement by covering of residue storage tanks

A gas-tight covering of residue storage tanks contributes to the avoidance of methane emissions and enables utilisation of the biogas of the residue storage tank. As a result, less feedstock is needed for the same energy output, furthermore, less current expenses contribute to a more profitable business.

Table 5.7 shows the effects of utilising the remaining biogas potential for two biogas plants, each with an electric capacity of 500 kW_{el}. The substrate conversion efficiency of biogas plant A is assumed to be increased by 1 percentage point (1 percentage point of remaining biogas potential usable), the conversion efficiency of biogas plant B is increased by 3 percentage points (3 percentage points of remaining biogas potential usable).

Table 5.7: Effects of using the remaining biogas potential

Biogas Plant			**A**	**B**
Electric Capacity		[kW_{el}]	500	
Improved Substrate Conversion Efficiency		[percentage points]	1	3
Effects	Required Substrate (maize silage)	[t/a]	- 109	- 327
	Required Farmland	[ha]	- 2	- 6
	Substrate Costs	[€/a]	- 3,800	- 11,400
	GHG emissions (maize silage)	[$kg_{CO2\text{-}Eq.}$/a]	- 3,888	- 11,664
	GHG emissions (methane)	[$kg_{CO2\text{-}Eq.}$/a]	- 195,932	- 587,797

By covering the residue storage tank of biogas plant A, methane emissions of approx. 10,950 m³/a can be avoided, while a gas-tight covering of biogas plant B can reduce methane emissions by approx. 32,850 m³/a. The required amount of substrate can be reduced at both biogas plants, leading to a substrate cost saving of approx. 3,800 €/a (biogas plant A) and 11,400 €/a (biogas plant B).

All these calculations are based on the following assumptions: a methane content of biogas of 53 %, an electrical efficiency of the CHP-Unit of 38.5 %, a maize yield of 50 t/ha and a substrate cost (maize silage) of 35 €/t.

As a result of the reduction of both the methane emissions and feedstock necessary, biogas plant A avoids 199 $t_{CO2\text{-}Eq.}$/a, which is equivalent to the GHG emissions of approx. 18 persons per year. Biogas plant B reduces GHG emissions by approx. 599 $t_{CO2\text{-}Eq.}$/a, equivalent to the emissions of approx. 53 persons per year.

Figure 5.3 shows the potential for savings per year, if the residue storage tanks are covered, the remaining biogas potential utilised, and the amount of required substrates reduced. The savings can be determined individually (biogas plant A and B are already marked).

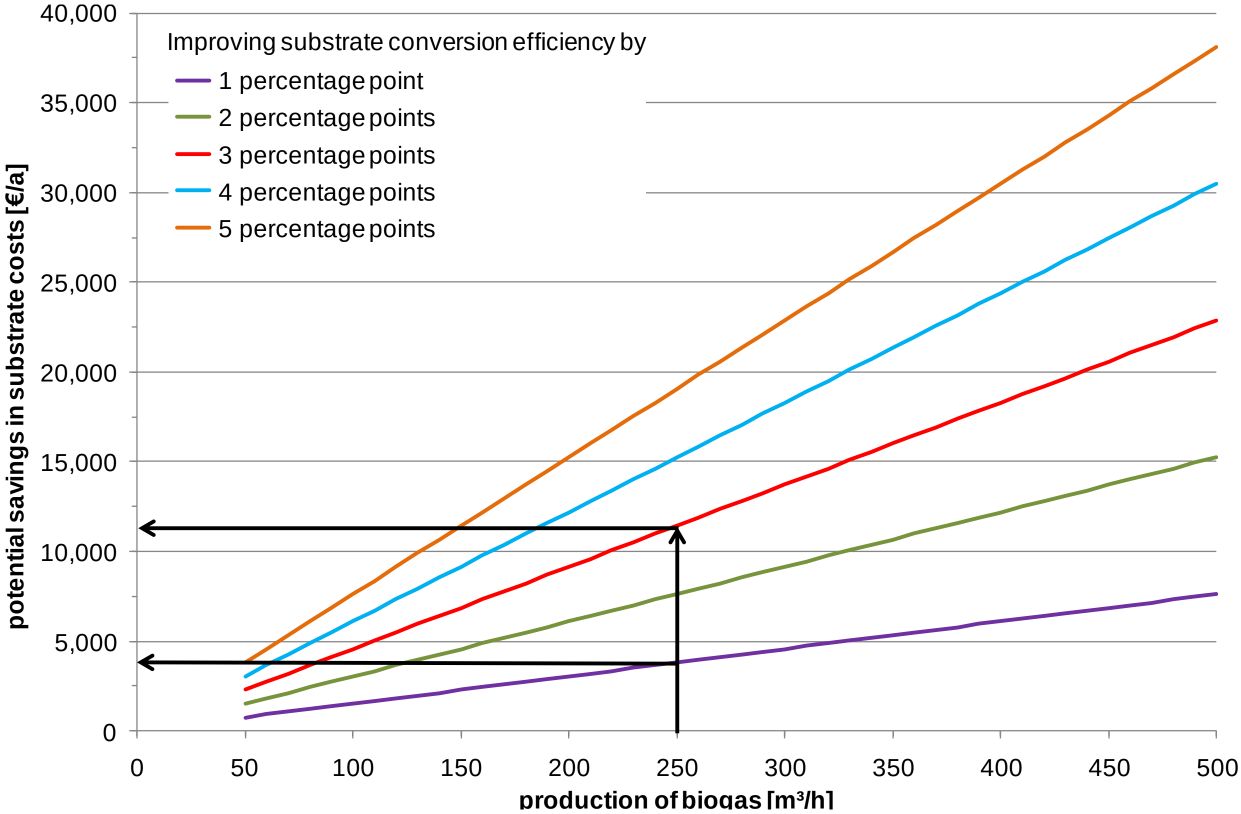


Figure 5.3: Potential for saving substrate costs via usage of the remaining biogas potential

A gas-tight covering of residue storage tanks increases climate protection in any case, however, the profitability depends on the particular remaining biogas potential and the investment requirements. As an alternative to reducing feedstock consumption, the energy output can be increased. Thus, there is potential for shorter payback periods for investments. It is also important to clarify additional costs for grid integration and approval before considering this approach.

5.5 Lowering Desulphurisation Electric Energy Consumption via Air Injection

Biological desulphurisation within the digester via air injection is considered to be an inexpensive as well as a reliable and low-maintenance solution. With this method, the hydrogen sulphide content can be reduced effectively.

The biogas plants` desulphurisation electric energy consumption (DEEC) can be calculated. A comparison of the various energy demands for injecting air into the digester of the analysed biogas plants shows that the energy demand cannot be attributed to plant-specific factors (e.g. injected air flow, growing layer for sulphur bacteria).

Higher specific DEEC is generally identified at smaller plants and can be traced back to inadequate dimensioning and design of the air injection system (e.g. oversized air blowers, use of air compressors).

Equation 5.1 can be used to calculate the specific DEEC:

$$E_{spec.\ desulphurisation} = \frac{P_{el,\ desulphurisation} \cdot t_{desulphurisation,\ h}}{\dot{V}_{biogas,\ h}} \qquad 5.1$$

with

$E_{spec.\ desulphurisation}$	specific desulphurisation electric energy consumption	$\left[\frac{kWh_{el}/d}{Nm^3/h}\right]$
$P_{el,\ desulphurisation}$	electric power desulphurisation	$[kW_{el}]$
$\dot{V}_{biogas,\ h}$	biogas volume flow	$[Nm^3/h]$
$t_{desulphurisation,\ h}$	runtime of desulphurisation	[h/d]

The DEEC must not exceed 0.05 $(kWh_{el}/d)/(Nm^3/h)$.

Oversized Air Blowers

Figure 5.4 shows an oversized air blower with a nominal electric capacity of 540 W_{el}. To limit the injected air flow to the required 70 l/min, the ball valve is almost closed. This biogas plant with a biogas flow of 85 Nm^3/h consumes three times more electric energy (0.149 $(kWh_{el}/d)/(Nm^3/h)$) for desulphurisation than the target value, which results in an electricity cost of about 710 €/a (assuming 0.15 €/kWh_{el}).

To save on electric energy consumption, either the air blower can be replaced by a correctly dimensioned air blower, or a timer can be installed to limit the runtime of the oversized air blower.

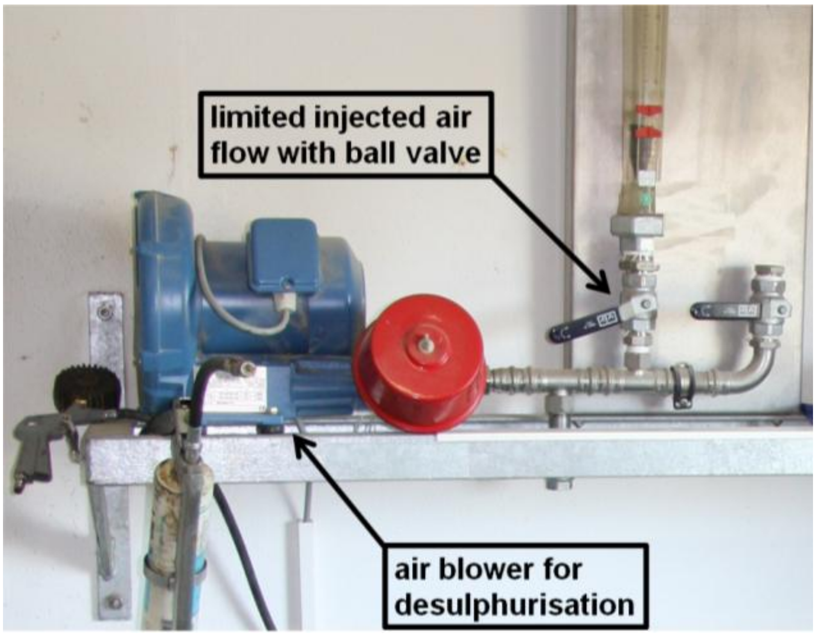


Figure 5.4: Oversized air blower for desulphurisation

For example, an air blower with a nominal electric capacity of 85 W_{el} can be used as an alternative. Using this 85 W_{el} device in the previously mentioned biogas plant will result in a specific DEEC of only 0.024 (kWh_{el}/d)/(Nm^3/h). This is equivalent to an electricity cost of € 112, which means a saving of about € 600 per year. In comparison to the annual saving, the initial investment is just € 350.

Besides the savings in electric energy and costs, a reduction of emissions of about 2,500 $kg_{CO2\text{-}Eq}$/a (emissions of the German electricity grid: 630 $g_{CO2\text{-}Eq}$/kWh_{el}) is also achieved. This is equivalent to the emissions of a car driving about 14,000 km.

Air Injection via Air Compressor

In some cases, the injection of air is realised by air compressors. Initially, this method seems to make sense because air compressors are required to run the pneumatic valves of pumping stations.

However, air compressors supply air at high pressure, and this pressure must be lowered before the air is injected into the digester. This results in a high percentage of waste energy.

The following example shows how much energy is wasted by using air compressors for desulphurisation.

For the biological desulphurisation of biogas at a flow rate of 115 Nm³/h, an air compressor is used which injects 90 l/h. About 2/3 of the pressurised air is used for desulphurisation, as shown in Figure 5.5 and Figure 5.6. Every day, 14 kWh_{el} are consumed to produce the required air flow. This means a specific DEEC of 0.12 (kWh_{el}/d)/(Nm³/h), which is equivalent to a payment of € 767 for electricity per year, assuming an electricity price of 0.15 €/kWh_{el}.

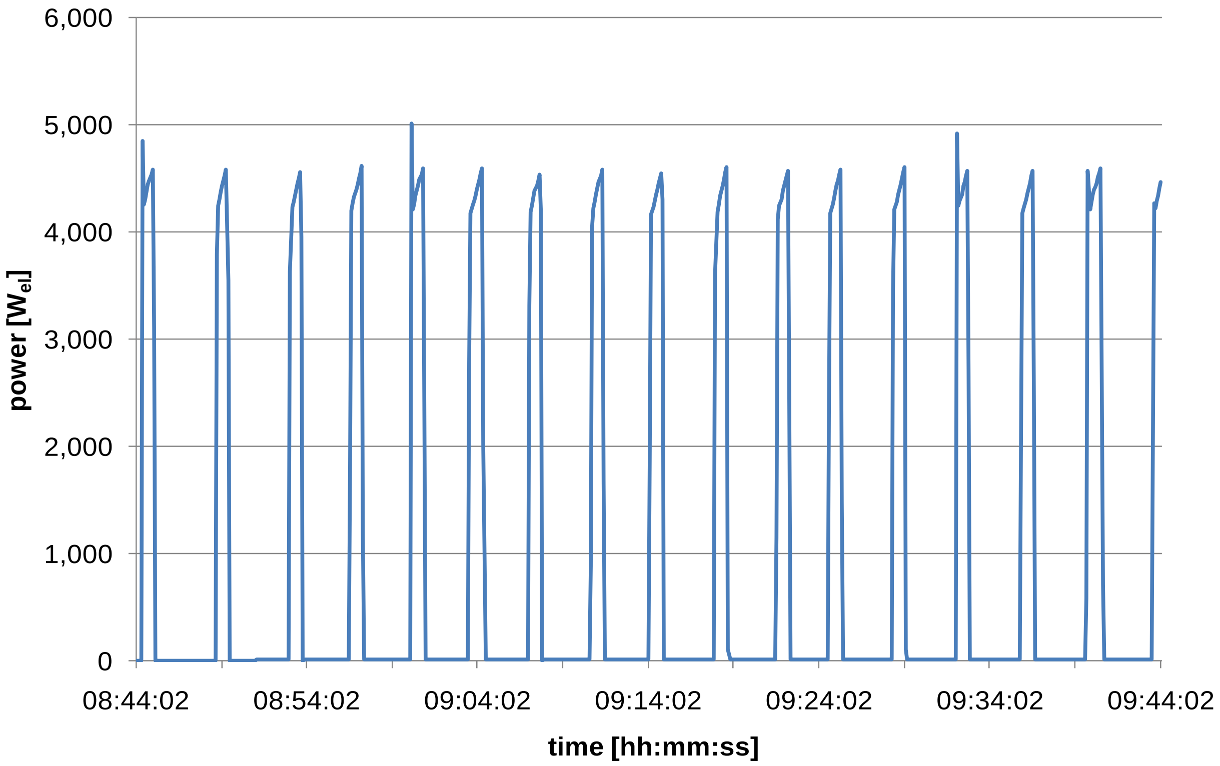


Figure 5.5: Power consumption of an air compressor providing air for desulphurisation and pneumatic valves of a pumping station

If the air compressor is replaced with an air blower (nominal electric capacity: 95 W_{el}, investment: € 350...400), the specific DEEC is reduced to 0.02 (kWh_{el}/d)/(Nm³/h). The equivalent payment for electricity is € 125, resulting in a saving of € 642 per year. Besides the saving of electric energy and cost, a reduction in emissions of about 2,700 kg $_{CO2\text{-}Eq}$/a is also achieved. This is equivalent to the emissions of a car driving about 15,000 km.

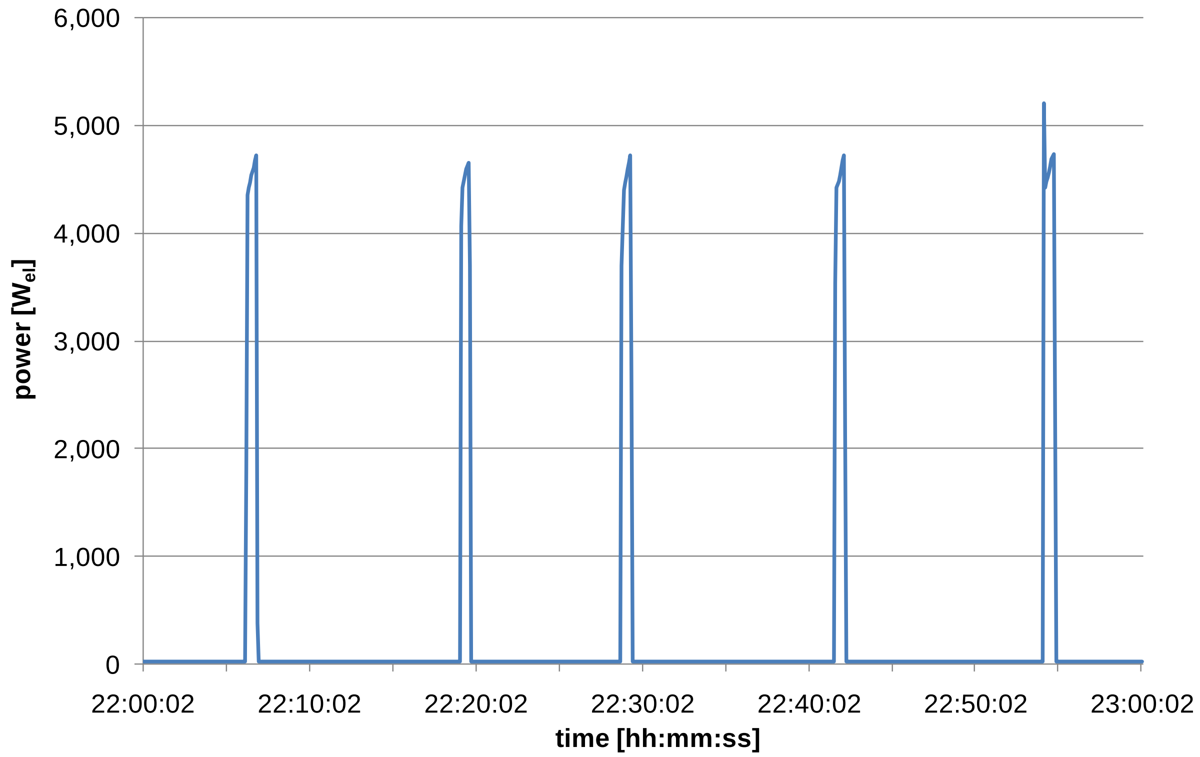


Figure 5.6: Power consumption of an air compressor without provision of air for desulphurisation

5.6 Improving Heat Utilisation via a Structured Planning Approach

CHP-Units produce electricity and heat at the same time. The utilisation of heat is a good way to optimise the economy and ecology of biogas plants. If this heat is only utilised for minor consumers, such as heating digesters and a low number of residential buildings or farm buildings, large quantities of heat remain unused.

An extensive utilisation of heat is tantamount to a maximum usage of feedstock and farmland. Furthermore, there is an ecological benefit due to the reduced consumption of fossil fuels, which improves the greenhouse gas balance of the plant.

Because of the possibility of an expected price increase for feedstock, all options to generate income have to be exploited. The utilisation and sale of heat contributes to a more profitable businesses. This is due to the fact that, in addition to the cogeneration bonus, heat can be sold directly. Thus, an EEG-independent income can be earned.

Minor heat utilisation can be traced back to the rural and exposed location of biogas plants. Thus, large investments are necessary to supply high-density settlements or industrial applications.

The main components of a CHP-Unit include the engine, generator and heat exchangers (Figure 5.7). Heat can be extracted from the engine cooling circuit, the exhaust gas and the charge air cooler. The coolant for the engine and charge air cooler has a temperature range of 80...90 °C. In most cases, plate heat exchangers are used for this temperature range. The exhaust gas has a temperature range between 400 °C and 600 °C. For the transfer of heat at these high temperatures, shell and tube heat exchangers are utilised. Due to the high temperature of the exhaust gas, steam and water at high temperatures can be produced.

Figure 5.7: Heat exchanger

CHP-Units have a thermal efficiency of 41...45 %. The amount of heat extracted from the exhaust gas contributes to about 40...45 % of the thermal output. CHP-Units are biased towards electrical output, heat is permanently produced throughout the year as a kind of by-product. If this heat is to be used for other processes, it has to be noted, that a considerable amount of heat is necessary to keep the biochemical process running during winter times.

District heating systems are a common way to supply heat to further consumers. Worthwhile heat consumers for biogas plants are those, which purchase uniform heat quantities throughout the year. These include swimming pools, manufacturing industries, buildings with an air conditioning demand and high-density settlements.

If the construction of district heating systems does not make commercial sense, there is still the alternative of a local biogas grid. Such a grid ensures the provision of biogas to potential consumers, pressure drops or temperature losses, typical for district heating systems, can almost completely be avoided.

Projects for the supply to further heat consumers run a high technical and economic risk, e.g. the heat demand (peak load) has to be covered at any time (Figure 5.8). However, adequate dimensioning of the heat exchangers ensures the required supply flow temperature.

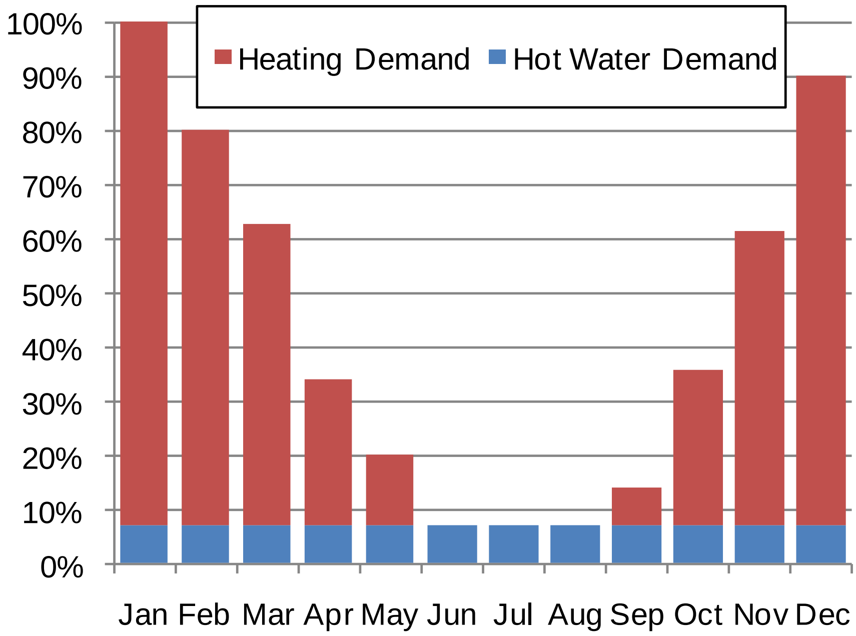


Figure 5.8: Typical heat demand of a multi-storey residential building

Figure 5.9 shows basic issues, which must be considered for an economic evaluation.

Because of the limited potential for improvement of heat utilisation with already existing biogas plants, a complete usage of heat must be aimed at during the conception and planning process.

Figure 5.9: Basic considerations for an economic evaluation before investing in an increased heat utilisation

5.7 Improving Heat Utilisation by Implementing Heat Meters

Some of the investigated biogas plants utilise the produced heat but do not measure it via a heat meter. For this reason, these biogas plants cannot receive the cogeneration bonus.

In order to qualify for the cogeneration bonus after commissioning, it is necessary to install officially calibrated heat meters for the recording of utilised heat. Heat meters consist of a volume flow meter and a temperature sensor, in both the supply and return flows (Figure 5.10).

The cost of heat meters (volume flow metre, temperature sensors, official calibration, accessories) for different flow rates varies between € 300 and € 1,300 (Table 5.8). The installation cost of a heat meter is € 300...400.

A further precondition for the cogeneration bonus is the so-called “environmental verification”. The verification is carried out by an independent expert, who audits whether the relevant legislative specifications are met to receive the cogeneration bonus. This process costs about € 800...1,300. In most cases, the additional earnings of the cogeneration bonus by far exceed the investment for the installation of heat meters.

Figure 5.10: Heat meters (Heat meter 2010)

Table 5.8: Costs of heat meters at different flow rates

Nominal Flow	**Net Cost**
[m³/h]	[€]
3.5	300…380
6	300…380
10	450…500
15	750…850
25	800…900
40	850…950
60	1,000…1,200
100	1,100…1,300

It must be noted that the compensation and application of the cogeneration bonus is categorised into two different types:

- Biogas plants put into operation after 01.01.2009 must fulfil the requirements of the EEG 2009 to receive a cogeneration bonus of 3 ct/kWh. These requirements can be found in appendix 3 of the EEG 2009. There, a positive and negative list for the use of heat is included.
- Biogas plants put into operation before 01.01.2009 can select between the co-generation bonus of the EEG 2009 (3 ct/kWh) and the EEG 2004 (2 ct/kWh). As a precondition for the cogeneration bonus of the EEG 2004, it must be noted, that the heat usage must have been put into operation before 01.01.2009.

The economic benefit of a retrofit in order to receive the cogeneration bonus is shown in the following example.

A biogas plant with an electric capacity of 100 kW_{el} was put into operation in 2001. It supplies three residential buildings with heat, a heat meter is already installed. The only requirement remaining to qualify for the cogeneration bonus is the environmental verification. Figure 5.11 shows that the investment for the environmental verification has a payback period of less than six months. After the first year, an additional revenue of € 3,100 can be achieved, which results in a profit € 1,800.

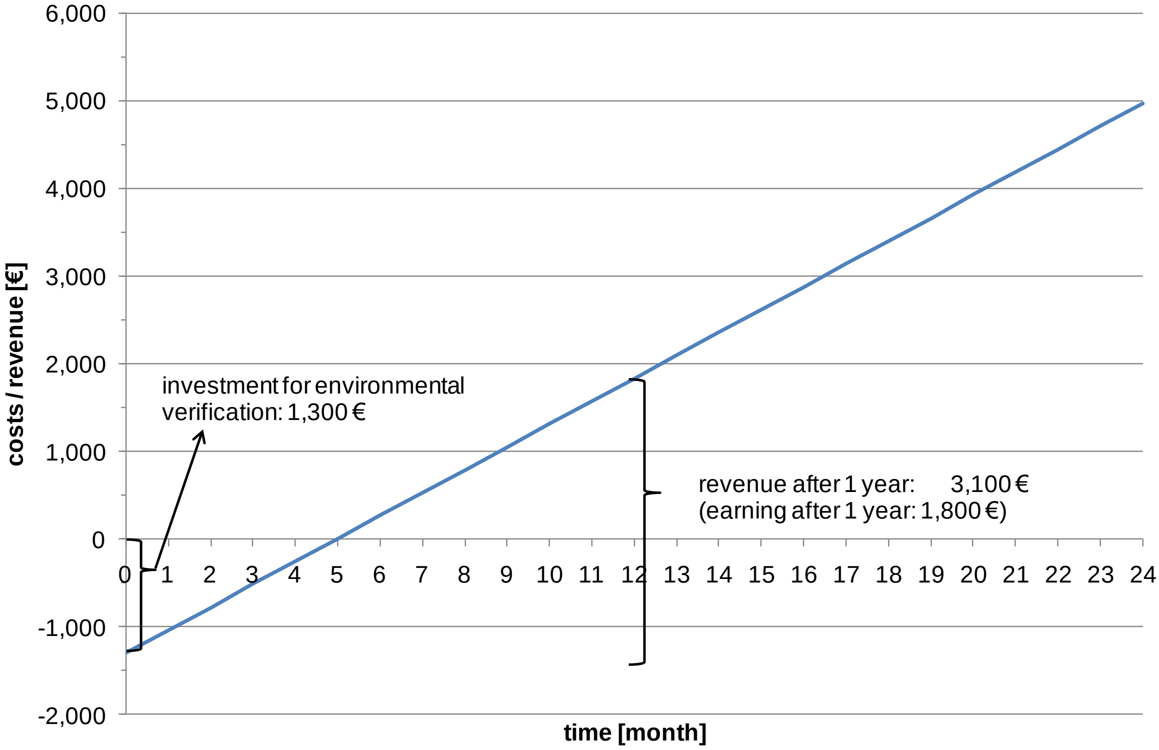


Figure 5.11: Costs and revenue for the retroactive utilisation of heat at a 100 kW_{el} biogas plant

Process Heat Measurement

For the optimisation of biogas plants, it is also recommended to measure the process heat demand. Thus, the heat consumption of the digesters can be verified, as a result, the amount of heat available for commercial use can be determined.

5.8 Improving Utilisation of the CHP-Unit

A high utilisation of the CHP-Unit is an important factor for the profitability of biogas plants. High CHP-Unit utilisation is achieved by correct operation of the biogas plant, therefore, maintenance schedules have to be met consequently and the plant has to be appropriately monitored (Figure 5.12).

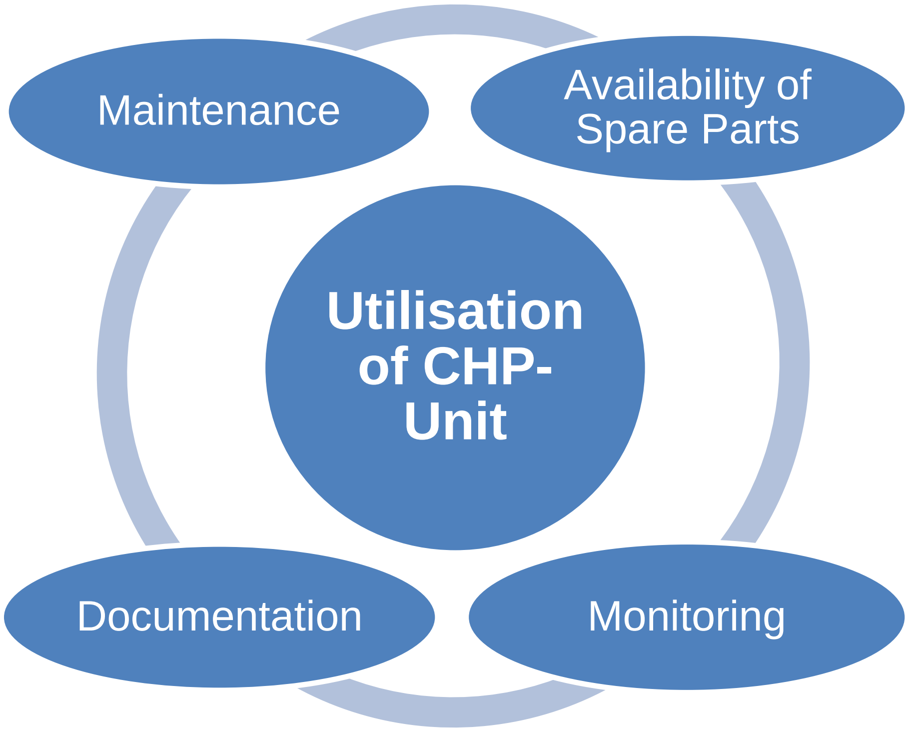


Figure 5.12: Factors influencing the utilisation of a CHP-Unit

High utilisation of the CHP-Unit can be achieved by following these recommendations:

- Strictly and consistently comply with maintenance schedules (Table 5.9).
- Have spare parts for critical components such as feeding system, agitators, pumps and CHP-Unit available.
- Monitor the biogas plant via measurement equipment and external tests
    - substrate (weighing of substrate),
    - digester (temperature, pH value, fill level digester, VOA/TIC, organic acid),
    - biogas (composition, gasholder fill level, amount of produced biogas, hydrogen sulphide),
    - CHP-Unit (runtime, electric output, thermal output, analysis of oil quality).
- Regularly record data in the operational log to ensure detection of abnormalities.

The following two examples show the additional earnings due to improved CHP-Unit utilisation (Table 5.10). Biogas plant A (electric capacity: 175 kW_{el}, current utilisation: 93 %) can reach additional earnings of approx. € 10,000 by increasing its CHP-Unit utilisation to 97 %. Biogas plant B (electric capacity: 320 kW_{el}, current utilisation: 80 %) can achieve additional earnings of approx. € 86,000.

Table 5.9: Checklist for the operation of a biogas plant (Weiland et al. 2009)

Interval	Task
Daily	• Recording of CHP-Unit output, electricity output and operating hours • Recording of biogas flow, control of biogas quality and biogas pressure • Ignition oil consumption (if applicable), engine oil fill level, engine oil temperature • Monitoring of fermentation process temperature • Controlling of water pressure within the heating systems • Monitoring of biological parameters and pH value • Functional check of desulphurisation unit and air blower • Checking of desulphurisation performance and amount of air added (max. 6 % Vol.) • Checking of stirring frequency (sinking and swimming layers?) • Checking of digester fill levels • Recording of parasitic electric energy (if applicable)
Weekly	• Moving all slide gates • Checking fill level of sealing liquid in pressure relief valves and steam traps, fill with antifreeze in case of frost (depending on the weather, a daily task) • Checking of overflows for deposits • Functional check of gas train (valves) • Checking of wires for damage • Checking of silo for leaks • Functional check of transmissions • Cleaning of easily soiled components
Monthly	• Removal of oil deposits from CHP-Unit, cleaning of oil tray • Checking of gas conducting systems for damages, leaks and corrosion (inspection with leakage detector)
Six-Monthly	• Checking of ventilation of engine room • Checking of electrical installations for damages • Functional check of gas sensors and fire detectors
Yearly	• Calibration of gas sensors

Table 5.10: Additional earnings from improved CHP-Unit utilisation

Biogas Plant			**A**	**B**
Electric Capacity		[kW_{el}]	175	320
Current Utilisation		[%]	93	80
Revenues by Basic Compensation	Current Utilisation	[€/a]	321,800	433,400
	At Utilisation Ratio of 97 %	[€/a]	331,800	519,200
Additional Earnings due to improved CHP-Unit Utilisation*		[€/a]	10,000	85,800

* Sale of heat and cogeneration bonus is possible

A CHP-Unit utilisation of more than 98 %, however, has to be considered as critical because of the high amount of biogas necessary to be stored. There is the risk of biogas losses to the atmosphere caused by an overproduction of biogas, which has to be avoided to protect the climate in any case.

6 Conclusions

The research demonstrated the possibility to improve ecology and economy of biogas plants by applying simple, low cost and quickly implementable solutions. By implementing the suggested solutions, both greenhouse gas emissions and current expenses can be reduced. Furthermore, the competition for farmland with the food production sector can be reduced. The optimisation concepts are based on the extensive investigation and analysis of 10 biogas plants in Bavaria. Within the project, a widespread and thorough data analysis was carried out. Based on this, the generated data were evaluated followed by a benchmark and error analysis. Knowing the problems of biogas plants finally led to the development of eight optimisation concepts aiming at the improvement of the ecology and economy of biogas plants.

In the course of the data-acquisition and -analysis, first of all, the 10 biogas plants had to be selected. The selection was based on a number of criteria such as different electric capacity and the variation of manufacturers. Hence, the heterogeneous conditions and realities encountered at the 10 biogas plants in Bavaria are representative for biogas plants found all over Germany. The analysis included temporary on-site measurements (e.g. parasitic electric energy, methane emissions) and a systematic recording of the biogas plants.

The evaluation and weak point analysis of the data generated was carried out following the complete production cycle from the substrate supply to the utilisation of biogas. For this purpose, key performance indicators were used to compare the plants with each other. The evaluation of the data showed a wide range of different weaknesses.

The identification of promising approaches for the optimisation of biogas plants was carried out following a new approach. Each area of investigation was rated according to its economic potential, its ecological potential and its potential for realisation. Areas of investigation with the highest score were selected for the development of the eight optimisation concepts:

1. Shortening of the distance between silo and feeding system
2. Improving substrate conversion by using highly efficient CHP-Units
3. Improving substrate conversion by avoiding biogas leaks

4. Reducing methane emissions and improving substrate conversion by covering residue storage tanks
5. Lowering desulphurisation electric energy consumption via air injection
6. Improving heat utilisation via structured planning approach
7. Improving heat utilisation by implementing heat meters
8. Improving utilisation of the CHP-Unit

These concepts show high potential for the ecological and economic optimisation of biogas plants. However, each biogas plant is planned individually according to its environmental conditions. Thus, no standard biogas plant can be defined. Due to that heterogeneity, the concepts have to be adapted individually. Nonetheless, the potential of the developed optimisation concepts can be described using characteristic values.

Given the optimisation concepts 1 to 5 are implemented at 20 % of the German biogas plants, an additional profit of about € 38,000,000 per year can be achieved. Furthermore, the greenhouse gas emissions can be reduced by about 470,000 $t_{CO2\text{-}Eq.}$/a, which is equivalent to the emissions of about 43,000 inhabitants, i.e. a small city, in Germany.

A very high potential for optimisation is an improved utilisation of heat, as described in 5.6 and 5.7. In case of a biogas plant with a capacity of 500 kW_{el}, a heat utilisation of 50 % leads to a turnover increase of about € 250,000 per year, based on a cogeneration bonus of 3 ct/kWh and a selling price of 6 ct/kWh. Emissions of about 900 $t_{CO2\text{-}Eq.}$/a can additionally be avoided by the substitution of conventional, fossil heat.

High utilisation of the CHP-Unit can be achieved by following the recommendations described in 5.8. An increased CHP-Utilisation by 10 percentage points at 20 % of the German biogas plants leads to a turnover increase of about € 83,500,000 per year.

To avoid faults in the future, the suggested solutions need to be taken into consideration already in the process of design of biogas plant systems and components as well as in the planning process. The production and utilisation of biogas has to become more efficient and flexible. This increase in efficiency and flexibility has to result in a reduction of the required feedstock and a controllable electricity production.

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Appendix A:

Data and Assumptions for the Greenhouse Gas Balances

Loads

Assumed emission factors of upstream and downstream processes (Vogt et al. 2008)

Source of Emission	Emission Factors
Cropping **Digestate Application**	Standard Values according to Vogt et al. (2008)

Assumed methane loss rates at biogas plants (Vogt et al. 2008)

Source of Methane Loss	Methane Loss Rate in comparison to the Produced Amount of Methane [%]
Foil Covering	0.5
Exhaust Gas of a Gas-CHP-Unit	0.5
Exhaust Gas of a Pilot-Injection-CHP-Unit	0.9
Remaining Biogas Potential in non-covered Residue Storage Tanks	2.5

Assumed methane emission factors for the storage of slurry (Umweltbundesamt 2002)

Type of Slurry	Methane Emissions [kg_{CH4}/m^3_{Slurry}]
Cattle Slurry	1.79
Cattle Manure	0.30
Pig Slurry	1.38

Assumed emission factor for ignition oil (Ecoinvent 2007 and Deutsche Emissionshandelsstelle 2007)

	Emissions [$kg_{CO2}/kWh_{Ignition\ Oil}$]
Ignition Oil	0.302

Credits

Assumed credits for energy produced from biogas (IFEU, Stoffstromtool Umberto®, Arbeitsgemeinschaft Energiebilanzen, Verband der Elektrizitätswirtschaft)

Emission Factor	Emissions [kg_{CO2}/kWh]
German Electricity Mix	0.630
Heat for Households	0.327

Appendix B:

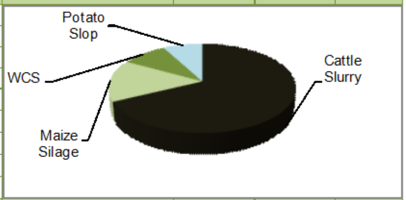
Biogas Plant

Data Sheets, Schematics

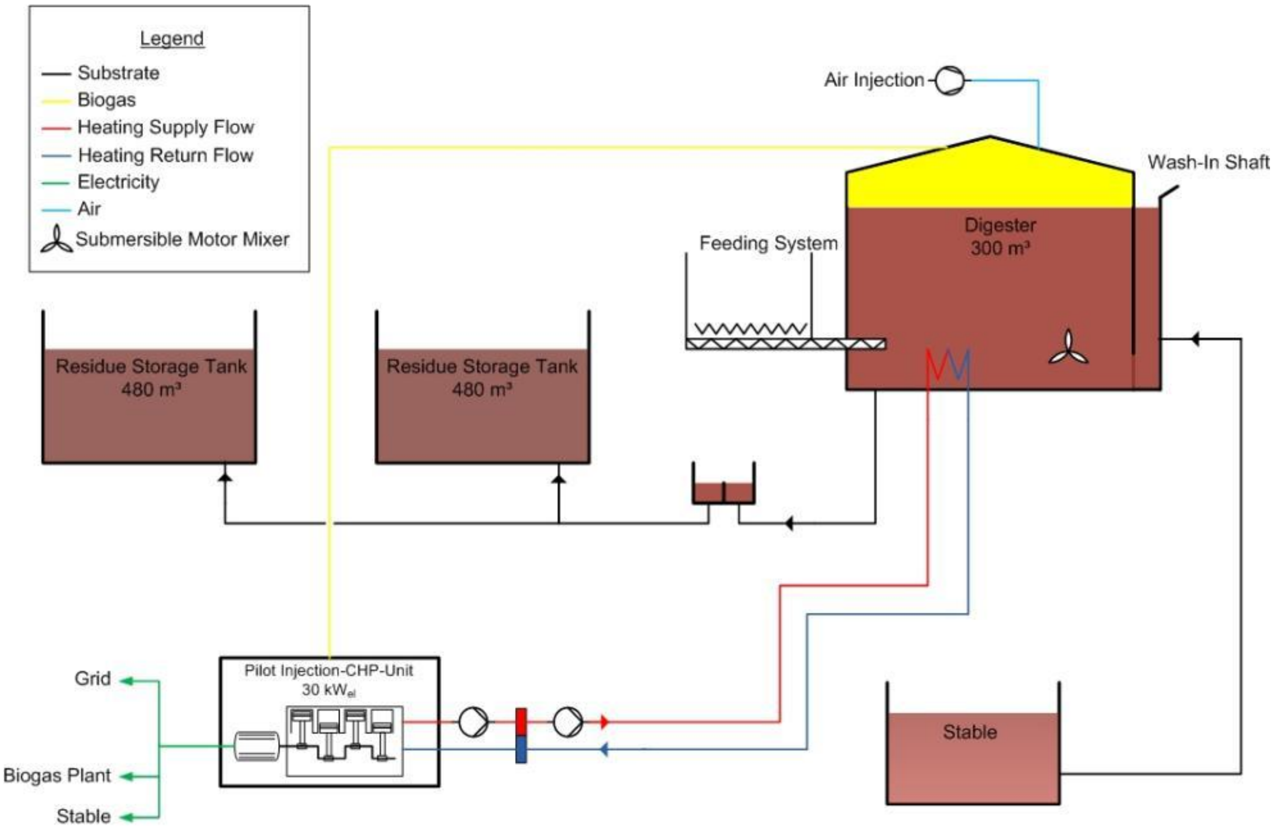
And Measurement Periods

2009						
Biogas Plant BY 1						
General						
Start of Operation	1999					
Planning/Construction	Do-it-yourself					
Farmland for Energy Crops	10 ha					
Livestock on Farm	66 LU Dairy Cattle					

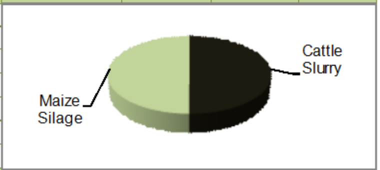
Substrate	[%]	[t/d]
Cattle Slurry	67.8	**4.4**
Maize Silage	15.2	1.0
WCS	9.1	0.6
Potato Slop	7.9	0.5
Total		**6.5**
mean Dry Matter*		
[% DM]	13.9	
mean organic Dry Matter*		
[% oDM]	88.8	

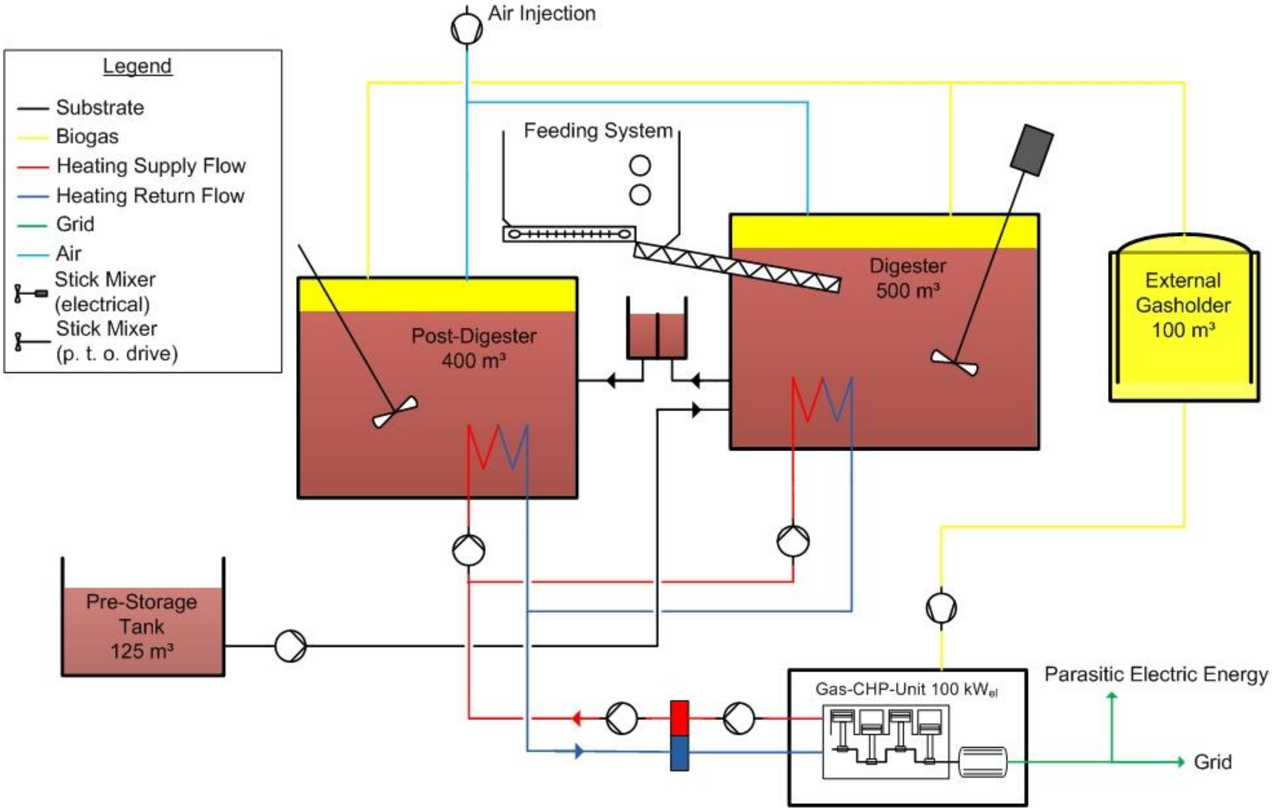


Operating Data		Digester	Residue Storage Tank			Total
Digestion Temperature	[°C]	39				
Active Digester Volume	[m³]	300	960			300
Added Substrate Mass	[t/d]	6				6
Added Substrate Volume	[m³/d]	7				7
Hydraulic Retention Time*	[d]	41				41
Volume Load	[kg $_{oDM}$/m³$_{active\ digester}$·d]					2.7
Specific Digester Volume	[m³/kW$_{el.\ capacity}$]					10
Biogas						
Composition	CH_4 [%]	CO_2 [%]	O_2 [%]	H_2S [ppm]	NH_3 [ppm]	
	52.2	40.3	0.8	33	8	
Methane Yield*	[Nm³/t$_{FM}$]	19.9				
Methane Productivity*	[Nm³/m³$_{active\ digester}$]	0.4				
CHP-Unit						Total
Number		1				
Manufacturer		Hochreiter				
Type		Pilot Injection				
Engine		John Deere				
Cylinder		4				
Displacement	[l]	3.9				
El. Efficiency***	[%]	32.0				
Th. Efficiency***	[%]	58.0				
El. Capacity**	[kW$_{el}$]	30				30
Th. Capacity	[kW$_{th}$]	-				0
Production of Electricity						Total
Mean Power Output	[kW$_{el}$]	24				24
CHP-Unit Utilisation	[%]	**81**				81
Theoretical CHP-Unit Utilisation	[h/a]	7,089				7,089
Gross Electricity Production***	[kWh$_{el}$/a]	212,665				212,665
Electricity Production per t $_{FM}$	[kWh$_{el}$/t$_{FM}$]	90				90
Heat Utilisation						
Heat Output*	[kWh$_{th}$/a]	**385,455**				
Process Heat*	[kWh$_{th}$/a]	**48,182**				
Utilised Heat Quantity	[kWh$_{th}$/a]	**0**				
Total Efficiency	η_{total}					
	[%]	**39**				
Parasitic Electric Energy						
Biogas Production Electric Energy Consumption	[kWh$_{el}$/d]	**19.1**				
CHP-Unit Electric Energy Consumption	[kWh$_{el}$/d]	**18.1**				
Total	[kWh$_{el}$/d]	**37.3**				
Parasitic Electric Energy	[%]	**6.4**				
Specific Stirring Electric Energy Consumption	[kWh$_{el}$/t$_{FM}$]	**1.9**				
Specific Stirring Electric Energy Consumption	[kWh$_{el}$/100m³$_{active\ digester}$]	**4.1**				
Feeding System Electric Energy Consumption without Slurry	[kWh$_{el}$/t$_{FM}$]	**1.1**				
Substrate Conversion Factor						
Factor	**[%]**	59				
*** calculated**						
**** according to manufacturer/datasheet**						
***assumption						

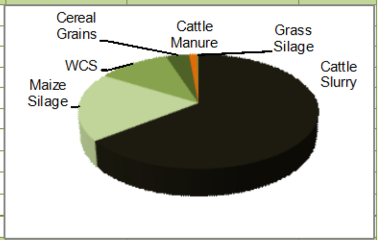


Biogas Plant BY 1			
Long-Term Data	Date	Start Time	End Time
Substrates Used		01.01.2009	31.12.2009
Electricity Production		23.12.2008	30.12.2009
Heat Utilisation	no utilisation		
On-Site Inspection / Communication with the Biogas Plant Operator			
Fundamental Structure	15.12.2009		
Operational Mode	15.12.2009		
Temporary On-Site Measurements			
Parasitic Electric Energy	19.03.2010		
Runtime of Each Component		02.04.2010	06.05.2010
Composition of Biogas	19.03.2010		
Methane Emissions	15.12.2009		
External Analysis			
Samples for Biochemical Analysis	15.12.2009		
Biochemical Analysis		16.12.2009	18.12.2009
Samples for Remaining Biogas Potential	no measurement		
Remaining Biogas Potential	no measurement		

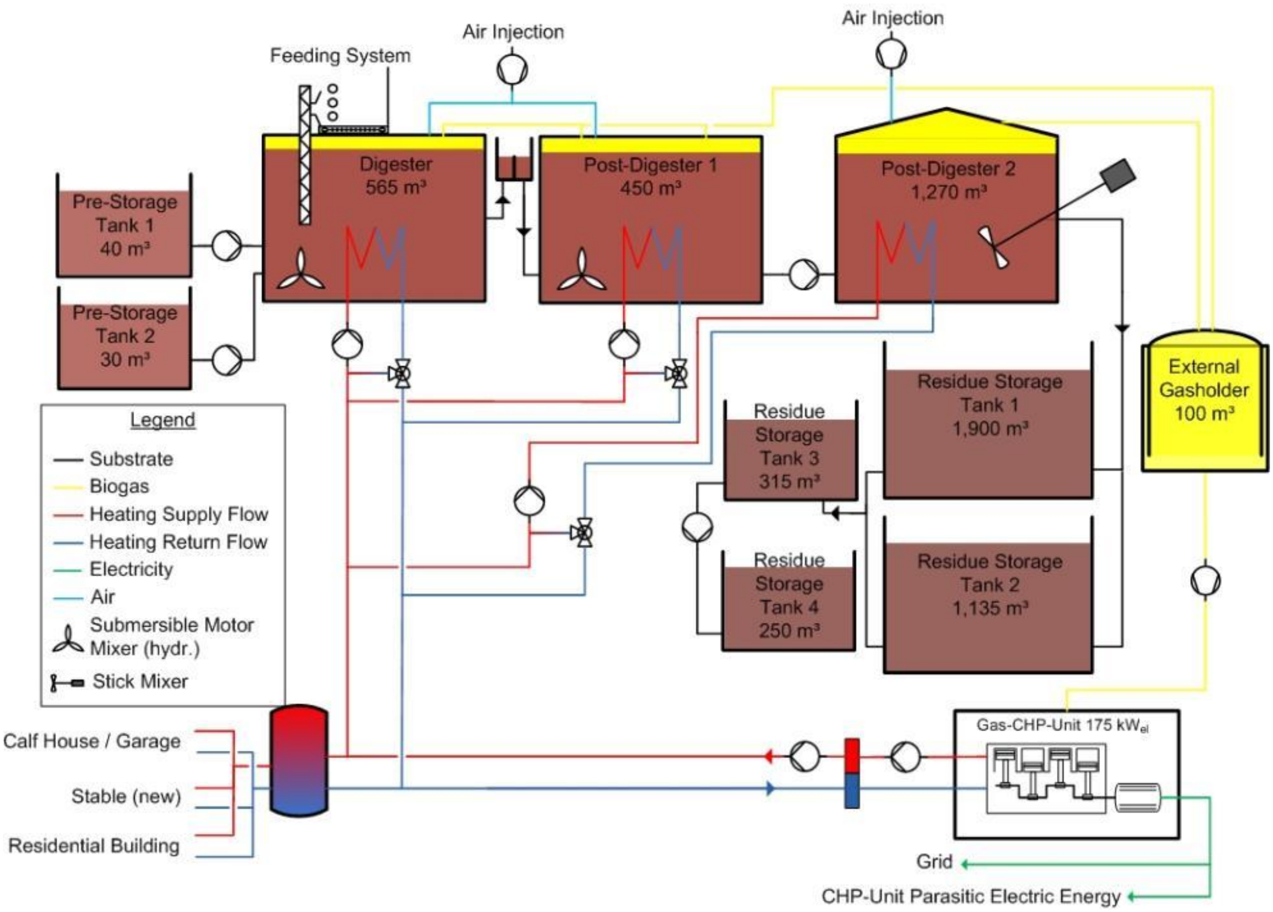
2009						
Biogas Plant BY 2						
General						
Start of Operation	2002					
Planning/Construction	Reenergie Kempten					
Farmland for Energy Crops	35 ha					
Livestock on Farm	87 LU Dairy Cattle					
Substrate	[%]	[t/d]				
Cattle Slurry	50.1	**4.9**				
Maize Silage	49.9	**4.9**				
Total		**9.7**				
mean Dry Matter*						
[% DM]	20.5					
mean organic Dry Matter*						
[% oDM]	92.1					
Operating Data		Digester	Post-Digester			Total
Digestion Temperature	[°C]	38	40			
Active Digester Volume	[m³]	500	400			900
Added Substrate Mass	[t/d]	10				10
Added Substrate Volume	[m³/d]	12				12
Hydraulic Retention Time*	[d]	42	34			76
Volume Load	[$kg_{oDM}/m^3_{active\ digester} \cdot d$]					2.0
Specific Digester Volume	[$m^3/kW_{el.\ capacity}$]					9
Biogas						
Composition	CH_4 [%]	CO_2 [%]	O_2 [%]	H_2S [ppm]	NH_3 [ppm]	
	48.0	46.8	2.1	167	336	
Methane Yield*	[Nm^3/t_{FM}]	63.7				
Methane Productivity*	[$Nm^3/m^3_{active\ digester}$]	0.7				
CHP-Unit						Total
Number		1				
Manufacturer		Hagl				
Type		Gas				
Engine		MAN				
Cylinder		6				
Displacement	[l]	6.87				
El. Efficiency**	[%]	36.9				
Th. Efficiency**	[%]	42.4				
El. Capacity	[kW_{el}]	100				100
Th. Capacity	[kW_{th}]	115				115
Production of Electricity						Total
Mean Power Output	[kW_{el}]	95				95
CHP-Unit Utilisation	[%]	**95**				95
Theoretical CHP-Unit Utilisation	[h/a]	8,330				8,330
Gross Electricity Production***	[kWh_{el}/a]	833,000				833,000
Electricity Production per t $_{FM}$	[kWh_{el}/t_{FM}]	234				234
Heat Utilisation						
Heat Output*	[kWh_{th}/a]	**957,950**				
Process Heat*	[kWh_{th}/a]	**119,744**				
Utilised Heat Quantity	[kWh_{th}/a]	**0**				
Total Efficiency	η_{total}					
	[%]	**42**				
Parasitic Electric Energy						
Biogas Production Electric Energy Consumption	[kWh_{el}/d]	**28.9**				
CHP-Unit Electric Energy Consumption	[kWh_{el}/d]	73.5				
Total	[kWh_{el}/d]	**102.4**				
Parasitic Electric Energy	[%]	4.5				
Specific Stirring Electric Energy Consumption	[kWh_{el}/t_{FM}]	**2.1**				
Specific Stirring Electric Energy Consumption	[$kWh_{el}/100m^3_{active\ digester}$]	2.3				
Feeding System Electric Energy Consumption without Slurry	[kWh_{el}/t_{FM}]	**0.2**				
Substrate Conversion Factor						
Factor	**[%]**	**109**				
*** calculated**						
**** according to manufacturer/datasheet**						
***assumption						



Biogas Plant BY 2			
Long-Term Data	Date	Start Time	End Time
Substrates Used		01.01.2009	24.07.2009
Electricity Production		01.01.2009	31.08.2009
Heat Utilisation		no utilisation	
On-Site Inspection / Communication with the Biogas Plant Operator			
Fundamental Structure	24.07.2009		
Operational Mode	24.07.2009		
Temporary On-Site Measurements			
Parasitic Electric Energy	24.07.2009		
Runtime of Each Component		28.09.2009	06.05.2010
Composition of Biogas	24.07.2009 28.09.2009		
Methane Emissions	24.07.2009 28.09.2009		
External Analysis			
Samples for Biochemical Analysis	28.09.2009		
Biochemical Analysis		29.09.2009	30.09.2009
Samples for Remaining Biogas Potential	10.02.2010		
Remaining Biogas Potential		12.02.2010	17.03.2010



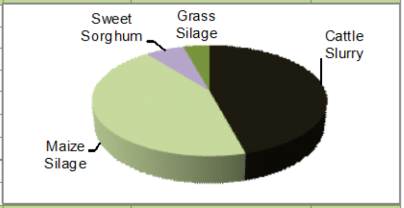
2009						
Biogas Plant BY 3						
General						
Start of Operation	2004					
Planning/Construction	UTS Biogastechnik GmbH					
Farmland for Energy Crops	93 ha					
Livestock on Farm	227 LU Dairy Cattle					
Substrate	[%]	[t/d]				
Cattle Slurry	64.5	13.3				
Maize Silage	19.3	**4.0**				
WCS	11.2	2.3				
Cereal Grains	3.6	0.7				
Cattle Manure	1.2	0.3				
Grass Silage	0.3	**0.1**				
Total		**20.7**				
mean Dry Matter*						
[% DM]	18.7					
mean organic Dry Matter*						
[% oDM]	91.0					
Operating Data		Digester	Post-Digester 1	Post-Digester 2	Residue Storage Tank	Total
Digestion Temperature	[°C]	42	42	**42**	-	
Active Digester Volume	[m³]	565	450	1,270	3,600	2,285
Added Substrate Mass	[t/d]	21				21
Added Substrate Volume	[m³/d]	24				24
Hydraulic Retention Time*	[d]	24	19	54		97
Volume Load	[kg $_{oDM}$/m³$_{active\ digester}$·d]					1.5
Specific Digester Volume	[m³/kW$_{el.\ capacity}$]					13
Biogas						
Composition	CH_4 [%]	CO_2 [%]	O_2 [%]	H_2S [ppm]	NH_3 [ppm]	
	51.7	40.8	1.6	308	5	
Methane Yield*	[Nm³/t$_{FM}$]	49.4				
Methane Productivity*	[Nm³/m³$_{active\ digester}$]	0.4				
CHP-Unit						Total
Number		1				
Manufacturer		Hagl				
Type		Gasmotor				
Engine		MAN				
Cylinder		6				
Displacement	[l]	12.8				
El. Efficiency**	[%]	38.5				
Th. Efficiency**	[%]	43.0				
El. Capacity***	[kW$_{el}$]	175				175
Th. Capacity***	[kW$_{th}$]	224				224
Production of Electricity						Total
Mean Power Output	[kW$_{el}$]	163				163
CHP-Unit Utilisation	[%]	**93**				93
Theoretical CHP-Unit Utilisation	[h/a]	8,179				8,179
Gross Electricity Production	[kWh$_{el}$/a]	1,431,283				1,431,283
Electricity Production per t $_{FM}$	[kWh$_{el}$/t$_{FM}$]	190				190
Heat Utilisation						
Heat Output*	[kWh$_{th}$/a]	**1,597,011**				
Process Heat*	[kWh$_{th}$/a]	**199,626**				
Utilised Heat Quantity	[kWh$_{th}$/a]	**459,847**				
Total Efficiency	η_{total}					
	[%]	**56**				
Parasitic Electric Energy						
Biogas Production Electric Energy Consumption	[kWh$_{el}$/d]	**113.5**				
CHP-Unit Electric Energy Consumption	[kWh$_{el}$/d]	144.6				
Total	[kWh$_{el}$/d]	**258.1**				
Parasitic Electric Energy	[%]	6.6				
Specific Stirring Electric Energy Consumption	[kWh$_{el}$/t$_{FM}$]	**4.2**				
Specific Stirring Electric Energy Consumption	[kWh$_{el}$/100m³$_{active\ digester}$]	3.8				
Feeding System Electric Energy Consumption without Slurry	[kWh$_{el}$/t$_{FM}$]	**0.5**				
Substrate Conversion Factor						
Factor	**[%]**	**97**				
*** calculated**						
**** according to manufacturer/datasheet**						
*** part-load operation (190kW$_{el}$)						



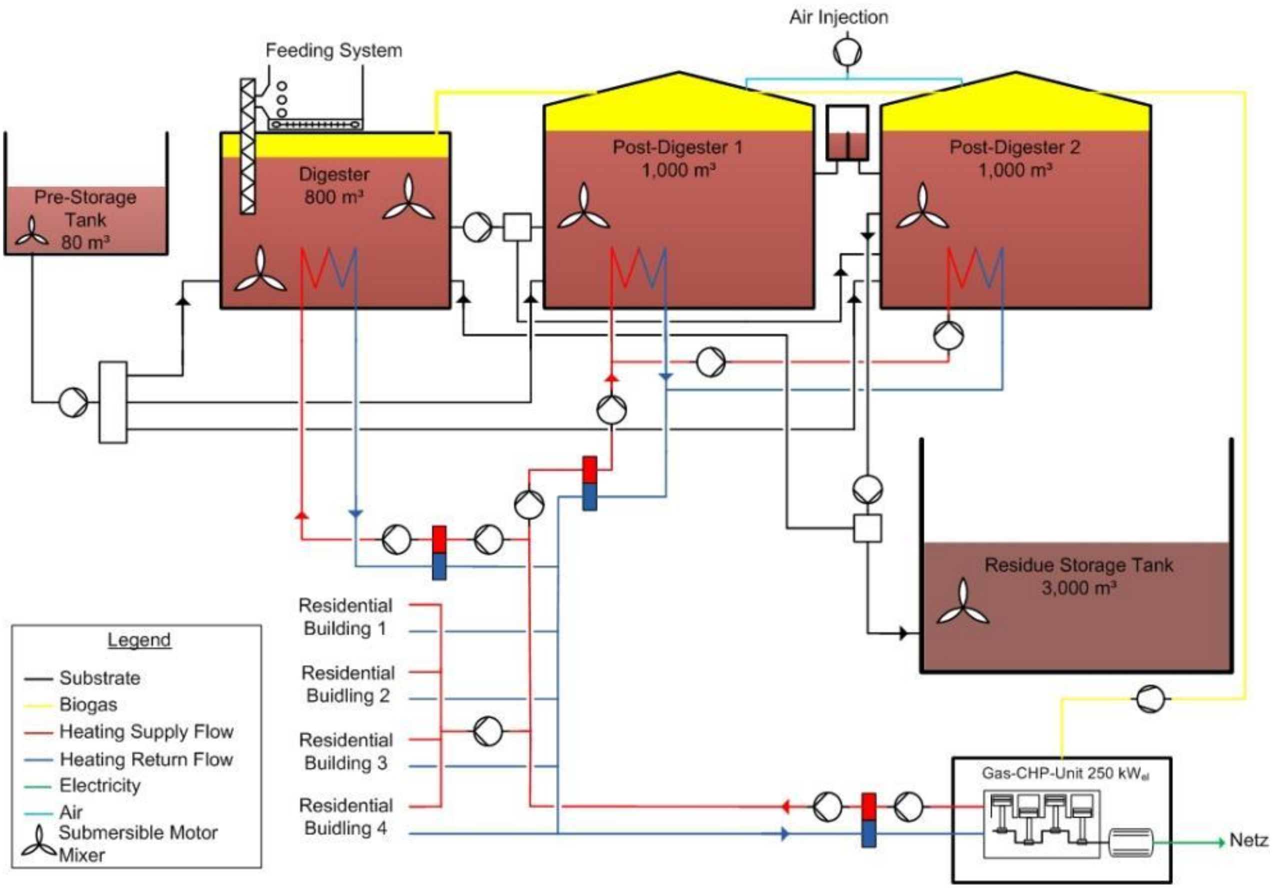
Biogas Plant BY 3			
Long-Term Data	Date	Start Time	End Time
Substrates Used		01.01.2009	31.12.2009
Electricity Production		01.03.2010	03.05.2010
Heat Utilisation		01.01.2009	31.12.2009
On-Site Inspection / Communication with the Biogas Plant Operator			
Fundamental Structure	03.05.2010		
Operational Mode	03.05.2010		
Temporary On-Site Measurements			
Parasitic Electric Energy		03.05.2010	04.05.2010
Runtime of Each Component		03.05.2010	28.05.2010
Composition of Biogas	26.01.2010		
Methane Emissions	04.05.2010		
External Analysis			
Samples for Biochemical Analysis	26.01.2010		
Biochemical Analysis		27.01.2010	28.01.2010
Samples for Remaining Biogas Potential	09.02.2010		
Remaining Biogas Potential		12.02.2010	17.03.2010

	2009					
Biogas Plant BY 4						
General						
Start of Operation	2005					
Planning/Construction	UTS Biogastechnik GmbH					
Farmland for Energy Crops	approx. 85 ha					
Livestock on Farm	200 LU Dairy Cattle					

Substrate	[%]	[t/d]
Cattle Slurry	45.8	**12.0**
Maize Silage	43.5	**11.4**
Sweet Sorghum	6.4	1.7
Grass Silage	4.3	1.1
Total		**26.2**
mean Dry Matter*		
[% DM]	20.9	
mean organic Dry Matter*		
[% oDM]	91.7	



Operating Data		Digester	Post-Digester 1	Post-Digester 2	Residue Storage Tank	Total
Digestion Temperature	[°C]	41	43	43		
Active Digester Volume	[m³]	800	1,000	1,000	3,000	2,800
Added Substrate Mass	[t/d]	26				26
Added Substrate Volume	[m³/d]	32				32
Hydraulic Retention Time*	[d]	25	32	32		89
Volume Load	[kg $_{oDM}$/m³$_{active\ digester}$·d]					1.8
Specific Digester Volume	[m³/kW$_{el.\ capacity}$]					11
Biogas						
Composition	CH_4 [%]	CO_2 [%]	O_2 [%]	H_2S [ppm]	NH_3 [ppm]	
	55.3	39.2	2.3	55	-	
Methane Yield*	[Nm³/t$_{FM}$]	57.1				
Methane Productivity*	[Nm³/m³$_{active\ digester}$]	0.5				
CHP-Unit						Total
Number		1				
Manufacturer		Hagl				
Type		Gas				
Engine		MAN				
Cylinder		8				
Displacement	[l]	14.62				
El. Efficiency**	[%]	38.5				
Th. Efficiency**	[%]	41.9				
El. Capacity**	[kW$_{el}$]	250				250
Th. Capacity**	[kW$_{th}$]	269				269
Production of Electricity						Total
Mean Power Output	[kW$_{el}$]	239				239
CHP-Unit Utilisation	[%]	**96**				96
Theoretical CHP-Unit Utilisation	[h/a]	8,379				8,379
Gross Electricity Production	[kWh$_{el}$/a]	2,094,793				2,094,793
Electricity Production per t $_{FM}$	[kWh$_{el}$/t$_{FM}$]	219				219
Heat Utilisation						
Heat Output*	[kWh$_{th}$/a]	**2,282,995**				
Process Heat*	[kWh$_{th}$/a]	**285,374**				
Utilised Heat Quantity	[kWh$_{th}$/a]	**313,900**				
Total Efficiency	η_{total}					
	[%]	**49**				
Parasitic Electric Energy						
Biogas Production Electric Energy Consumption	[kWh$_{el}$/d]	**183.4**				
CHP-Unit Electric Energy Consumption	[kWh$_{el}$/d]	142.2				
Total	[kWh$_{el}$/d]	**325.7**				
Parasitic Electric Energy	[%]	5.7				
Specific Stirring Electric Energy Consumption	[kWh$_{el}$/t$_{FM}$]	**5.2**				
Specific Stirring Electric Energy Consumption	[kWh$_{el}$/100m³$_{active\ digester}$]	4.8				
Feeding System Electric Energy Consumption without Slurry	[kWh$_{el}$/t$_{FM}$]	**1.1**				
Substrate Conversion Factor						
Factor	**[%]**	**97**				
*** calculated**						
**** according to manufacturer/datasheet**						

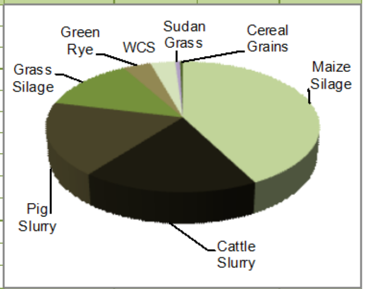


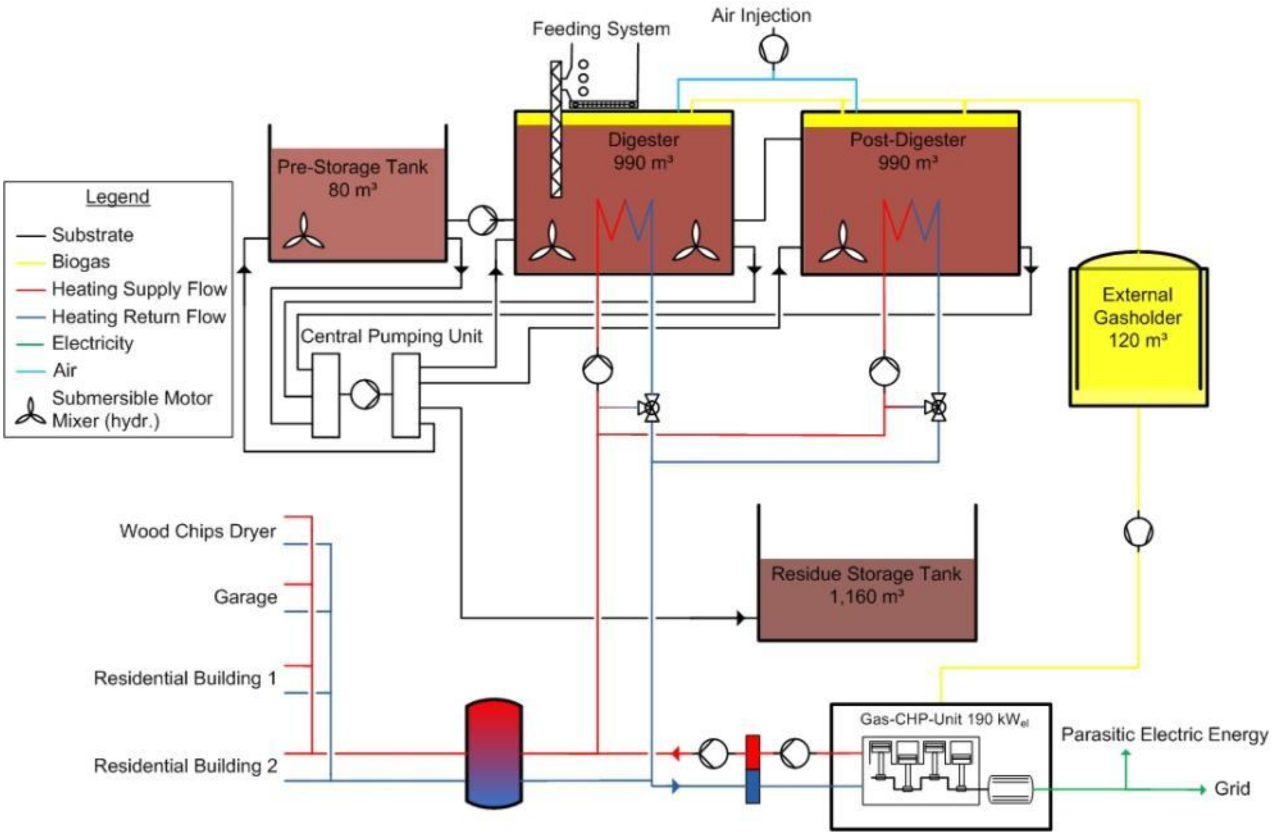
Biogas Plant BY 4			
Long-Term Data	Date	Start Time	End Time
Substrates Used		01.04.2009	31.07.2009
Electricity Production		01.04.2009	30.09.2009
Heat Utilisation		01.04.2009	30.06.2009
On-Site Inspection / Communication with the Biogas Plant Operator			
Fundamental Structure	15.10.2009		
Operational Mode	15.10.2009		
Temporary On-Site Measurements			
Parasitic Electric Energy	17.07.2009 20.07.2009 30.07.2009	07.01.2009	15.10.2009
Runtime of Each Component	monitoring unit		
Composition of Biogas	15.10.2009		
Methane Emissions	29.07.2009		
External Analysis			
Samples for Biochemical Analysis	29.07.2009		
Biochemical Analysis		31.07.2009	01.08.2009
Samples for Remaining Biogas Potential	09.02.2010		
Remaining Biogas Potential		12.02.2010	17.03.2010

2009

Biogas Plant BY 5

General						
Start of Operation	2005					
Planning/Construction	UTS Biogastechnik GmbH					
Farmland for Energy Crops	80 ha					
Livestock on Farm	35 LU Feeder Cattle					
Substrate	[%]	[t/d]				
Maize Silage	42.3	**5.8**				
Cattle Slurry	18.3	**2.5**				
Pig Slurry	18.2	2.5				
Grass Silage	13.0	1.8				
Green Rye	3.8	0.5				
WCS	3.4	0.5				
Sudan Grass	0.6	**0.1**				
Cereal Grains	0.4	**0.1**				
Total		**13.7**				
mean Dry Matter*						
[% DM]	23.6					
mean organic Dry Matter*						
[% oDM]	92.2					
Operating Data		Digester	Post-Digester	Residue Storage Tank		Total
Digestion Temperature	[°C]	40	40			
Active Digester Volume	[m^3]	990	990	1,160		1,980
Added Substrate Mass	[t/d]	14				14
Added Substrate Volume	[m^3/d]	20				20
Hydraulic Retention Time*	[d]	48	48			97
Volume Load	[kg $_{oDM}$/m^3 $_{active\ digester}$·d]					1.5
Specific Digester Volume	[m^3/$kW_{el.\ capacity}$]					10
Biogas						
Composition	CH_4 [%]	CO_2 [%]	O_2 [%]	H_2S [ppm]	NH_3 [ppm]	
	53.9	45.6	0.3	134	609	
Methane Yield*	[Nm^3/t_{FM}]	81.7				
Methane Productivity*	[$Nm^3/m^3_{active\ digester}$]	0.6				
CHP-Unit						Total
Number		1				
Manufacturer		Riemag				
Type		Gas				
Engine		MAN				
Cylinder		6				
Displacement	[l]	12.8				
El. Efficiency**	[%]	38.8				
Th. Efficiency**	[%]	47.8				
El. Capacity**	[kW_{el}]	190				190
Th. Capacity**	[kW_{th}]	235				235
Production of Electricity						Total
Mean Power Output	[kW_{el}]	181				181
CHP-Unit Utilisation	[%]	**95**				95
Theoretical CHP-Unit Utilisation	[h/a]	8,332				8,332
Gross Electricity Production	[kWh_{el}/a]	1,583,162				1,583,162
Electricity Production per t $_{FM}$	[kWh_{el}/t_{FM}]	316				316
Heat Utilisation						
Heat Output*	[kWh_{th}/a]	**1,950,390**				
Process Heat*	[kWh_{th}/a]	**243,799**				
Utilised Heat Quantity	[kWh_{th}/a]	**901,843**				
Total Efficiency	η_{total}					
	[%]	**67**				
Parasitic Electric Energy						
Biogas Production Electric Energy Consumption	[kWh_{el}/d]	**202.2**				
CHP-Unit Electric Energy Consumption	[kWh_{el}/d]	93.2				
Total	[kWh_{el}/d]	**295.4**				
Parasitic Electric Energy	[%]	6.8				
Specific Stirring Electric Energy Consumption	[kWh_{el}/t_{FM}]	**12.2**				
Specific Stirring Electric Energy Consumption	[$kWh_{el}/100m^3_{active\ digester}$]	8.5				
Feeding System Electric Energy Consumption without Slurry	[kWh_{el}/t_{FM}]	**0.6**				
Substrate Conversion Factor						
Factor	**[%]**	**116**				
*** calculated**						
**** according to manufacturer/datasheet**						

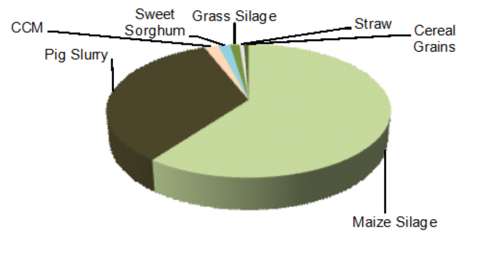




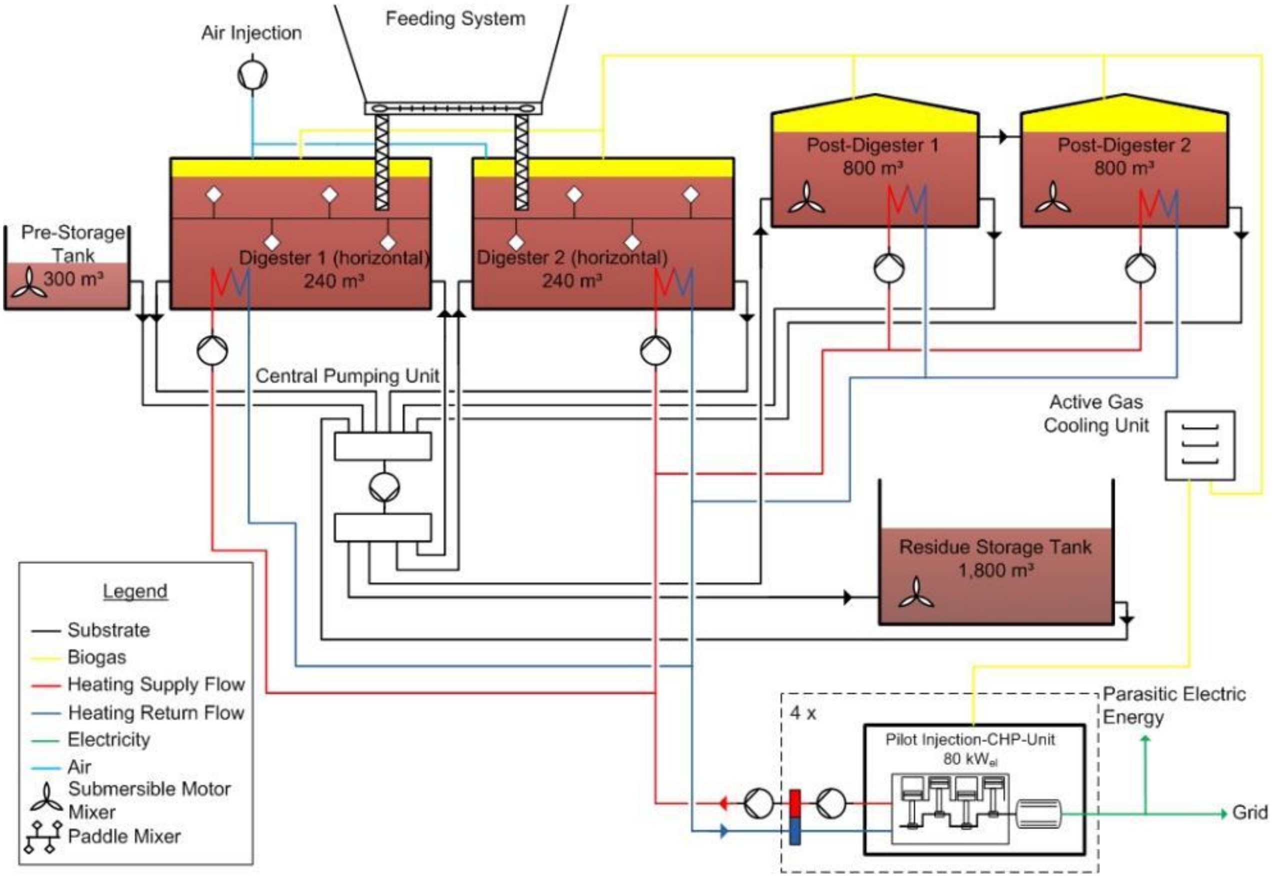
Biogas Plant BY 5			
Long-Term Data	Date	Start Time	End Time
Substrates Used		01.01.2008	31.12.2008
Electricity Production		01.01.2008	31.12.2008
Heat Utilisation		01.01.2008	31.12.2008
On-Site Inspection / Communication with the Biogas Plant Operator			
Fundamental Structure		23.04.2009	24.04.2009
Operational Mode		23.04.2009	24.04.2009
Temporary On-Site Measurements			
Parasitic Electric Energy	24.04.2009 28.04.2009 06.05.2009 07.05.2009		
Runtime of Each Component		07.05.2009	17.02.2010
Composition of Biogas	23.04.2009 24.04.2009 07.05.2009		
Methane Emissions	23.04.2009		
External Analysis			
Samples for Biochemical Analysis	16.02.2010		
Biochemical Analysis		18.02.2010	20.02.2010
Samples for Remaining Biogas Potential	17.02.2010		
Remaining Biogas Potential		19.02.2010	24.03.2010

2009

Biogas Plant BY 6



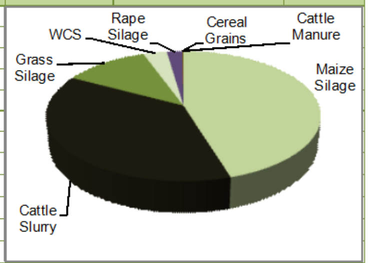
General							
Start of Operation	2001						
Planning/Construction	Schmack Biogas AG						
Farmland for Energy Crops	200 ha						
Livestock on Farm	260 LU, Pig Fattening						
Substrate	[%]	[t/d]					
Maize Silage	60.2	**15.3**					
Pig Slurry	33.9	**8.6**					
CCM	1.9	0.5					
Sweet Sorghum	1.6	0.4					
Gass Silage	1.3	0.3					
Straw	0.6	0.2					
Cereal Grains	0.6	0.2					
Total		**25.4**					
mean Dry Matter*							
[% DM]	25.1						
mean organic Dry Matter*							
[% oDM]	93.7						
Operating Data		Digester 1	Digester 2	Post-Digester 1	Post-Digester 2	Residue Storage Tank	Total
Digestion Temperature	[°C]	38	37	38	39		
Active Digester Volume	[m³]	240	240	800	800	1,800	2,080
Added Substrate Mass	[t/d]	13	13				26
Added Substrate Volume	[m³/d]	18	18				37
Hydraulic Retention Time*	[d]	13	13	**22**	**22**		56
Volume Load	[kg $_{oDM}$/m³$_{active\ digester}$·d]						2.9
Specific Digester Volume	[m³/kW$_{el.\ capacity}$]						7
Biogas							
Composition	CH_4 [%]	CO_2 [%]	O_2 [%]	H_2S [ppm]	NH_3 [ppm]		
	53.8	42.4	0.6	0	6		
Methane Yield*	[Nm³/t$_{FM}$]	58.3					
Methane Productivity*	[Nm³/m³$_{active\ digester}$]	0.7					
CHP-Unit							Total
Number		1	1	1	1		
Manufacturer		Schnell	Schnell	Schnell	Schnell		
Type		Pilot Injection	Pilot Injection	Pilot Injection	Pilot Injection		
Engine		-	-	-	-		
Cylinder		-	-	-	-		
Displacement	[l]	-	-	-	-		
El. Efficiency**	[%]	37.0	37.0	37.0	37.0		
Th. Efficiency**	[%]	44.0	44.0	44.0	44.0		
El. Capacity**	[kW$_{el}$]	80	80	80	80		320
Th. Capacity**	[kW$_{th}$]	95	95	95	95		380
Production of Electricity							Total
Mean Power Output	[kW$_{el}$]	64	64	64	64		256
CHP-Unit Utilisation	[%]	**80**	**80**	**80**	**80**		80
Theoretical CHP-Unit Utilisation	[h/a]	6,999	6,999	6,999	6,999		6,999
Gross Electricity Production	[kWh$_{el}$/a]	559,902	559,902	559,902	559,902		2,239,609
Electricity Production per t $_{FM}$	[kWh$_{el}$/t$_{FM}$]	240					240
Heat Utilisation							
Heat Output*	[kWh$_{th}$/a]	**2,663,319**					
Process Heat*	[kWh$_{th}$/a]	**332,915**					
Utilised Heat Quantity	[kWh$_{th}$/a]	**0**					
Total Efficiency	η_{total}						
	[%]	**43**					
Parasitic Electric Energy							
Biogas Production Electric Energy Consumption	[kWh$_{el}$/d]	**258.9**					
CHP-Unit Electric Energy Consumption	[kWh$_{el}$/d]	203.0					
Total	[kWh$_{el}$/d]	**461.9**					
Parasitic Electric Energy	[%]	7.5					
Specific Stirring Electric Energy Consumption	[kWh$_{el}$/t$_{FM}$]	**2.7**					
Specific Stirring Electric Energy Consumption	[kWh$_{el}$/100m³$_{active\ digester}$]	3.3					
Feeding System Electric Energy Consumption without Slurry	[kWh$_{el}$/t$_{FM}$]	**2.3**					
Substrate Conversion Factor							
Factor	**[%]**	**75**					
*** calculated**							
**** according to manufacturer/datasheet**							



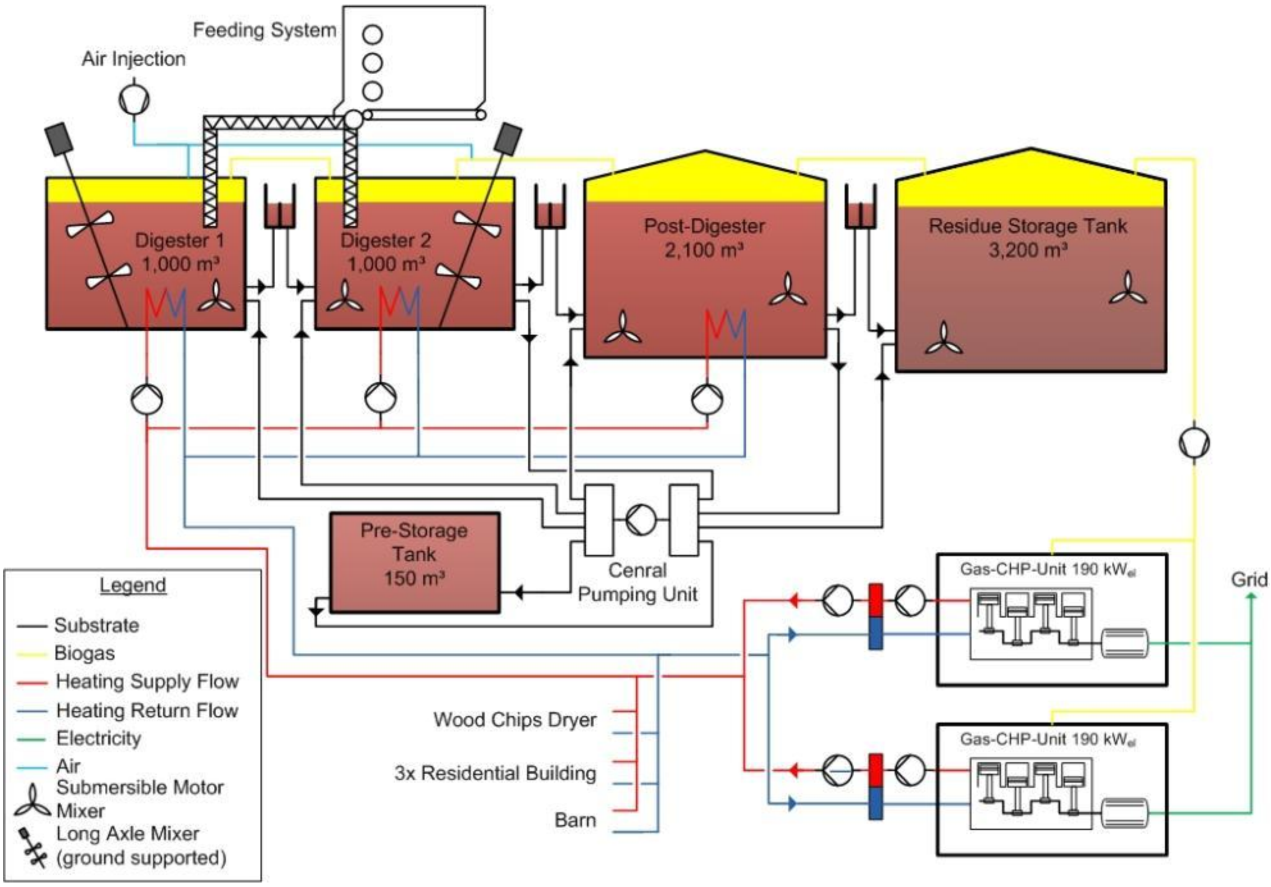
Biogas Plant BY 6			
Long-Term Data	Date	Start Time	End Time
Substrates Used		01.01.2009	31.12.2009
Electricity Production		01.01.2009	31.12.2009
Heat Utilisation	no utilisation		
On-Site Inspection / Communication with the Biogas Plant Operator			
Fundamental Structure	12.03.2010		
Operational Mode	12.03.2010		
Temporary On-Site Measurements			
Parasitic Electric Energy	12.03.2010 13.03.2010 16.04.2010 17.04.2010		
Runtime of Each Component	monitoring unit		
Composition of Biogas	12.03.2010		
Methane Emissions	16.04.2010		
External Analysis			
Samples for Biochemical Analysis	12.03.2010		
Biochemical Analysis		15.03.2010	17.03.2010
Samples for Remaining Biogas Potential	17.02.2010		
Remaining Biogas Potential		19.02.2010	24.03.2010

2009

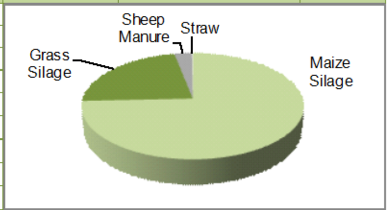
Biogas Plant BY 7

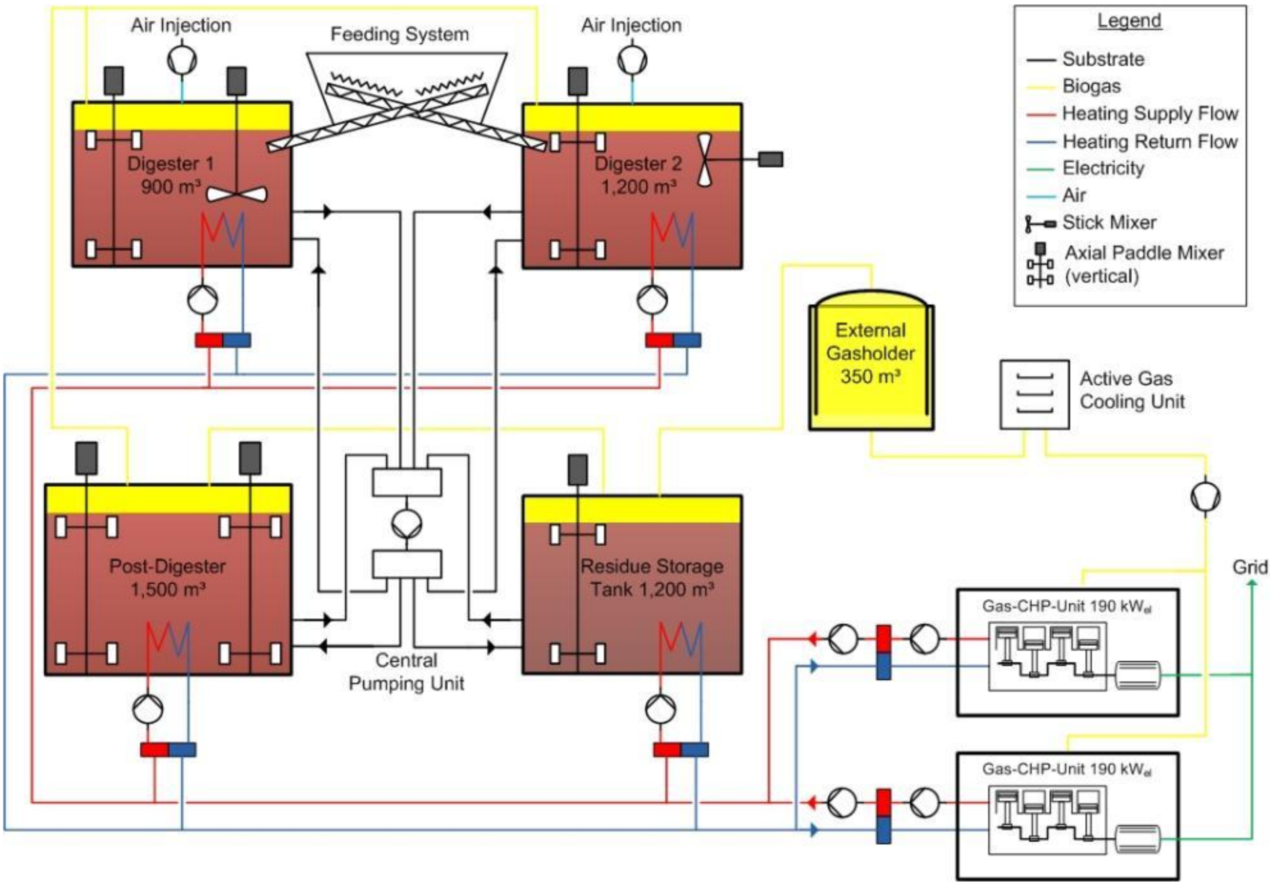


General						
Start of Operation	2005					
Planning/Construction	Regenerative Energien Planung und Bau, Gabriele Dyckhoff					
Farmland for Energy Crops	158 ha					
Livestock on Farm	130 LU Dairy Cattle					
Substrate	[%]	[t/d]				
Maize Silage	45.2	15.9				
Cattle Slurry	37.5	**13.2**				
Grass Silage	11.7	4.1				
WCS	3.3	1.1				
Rape Silage	2.1	0.7				
Cereal Grains	0.1	**0.0**				
Cattle Manure	0.0	**0.0**				
Total		**35.1**				
mean Dry Matter*						
[% DM]	23.5					
mean organic Dry Matter*						
[% oDM]	92.0					
Operating Data		Digester 1	Digester 2	Post-Digester	Residue Storage Tank	Total
Digestion Temperature	[°C]	39	39	**36**		
Active Digester Volume	[m³]	1,000	1,000	2,100	3,200	7,300
Added Substrate Mass	[t/d]	18	18			35
Added Substrate Volume	[m³/d]	25	25			51
Hydraulic Retention Time*	[d]	39	39	41	63	144
Volume Load	[$kg_{oDM}/m^3_{active\ digester}\cdot d$]					1.0
Specific Digester Volume	[$m^3/kW_{el.\ capacity}$]					19
Biogas						
Composition	CH_4 [%]	CO_2 [%]	O_2 [%]	H_2S [ppm]	NH_3 [ppm]	
	51.2	46.6	0.6	2	71	
Methane Yield*	[Nm^3/t_{FM}]	66.5				
Methane Productivity*	[$Nm^3/m^3_{active\ digester}$]	0.3				
CHP-Unit						Total
Number		1	1			
Manufacturer		Hagl	Hagl			
Type		Gas	Gas			
Engine		MAN	MAN			
Cylinder		6	6			
Displacement	[l]	12.8	**12.8**			
El. Efficiency**	[%]	38.6	38.6			
Th. Efficiency**	[%]	43.0	43.0			
El. Capacity**	[kW_{el}]	190	190			380
Th. Capacity**	[kW_{th}]	211	211			422
Production of Electricity						Total
Mean Power Output	[kW_{el}]	187	187			374
CHP-Unit Utilisation	[%]	**98**	**98**			98
Theoretical CHP-Unit Utilisation	[h/a]	8,615	8,615			8,615
Gross Electricity Production	[kWh_{el}/a]	1,636,930	1,636,930			3,273,860
Electricity Production per t_{FM}	[kWh_{el}/t_{FM}]	256	256			256
Heat Utilisation						
Heat Output*	[kWh_{th}/a]	**3,649,883**				
Process Heat*	[kWh_{th}/a]	**429,883**				
Utilised Heat Quantity	[kWh_{th}/a]	**3,220,000**				
Total Efficiency	η_{total}					
	[%]	**82**				
Parasitic Electric Energy						
Biogas Production Electric Energy Consumption	[kWh_{el}/d]	**266.6**				
CHP-Unit Electric Energy Consumption	[kWh_{el}/d]	**158.6**				
Total	[kWh_{el}/d]	**425.2**				
Parasitic Electric Energy	[%]	**4.7**				
Specific Stirring Electric Energy Consumption	[kWh_{el}/t_{FM}]	**6.2**				
Specific Stirring Electric Energy Consumption	[$kWh_{el}/100m^3_{active\ digeste}$	**3.0**				
Feeding System Electric Energy Consumption without Slurry	[kWh_{el}/t_{FM}]	**1.2**				
Substrate Conversion Factor						
Factor	**[%]**	**97**				
*** calculated**						
**** according to manufacturer/datasheet**						



Biogas Plant BY 7			
Long-Term Data	Date	Start Time	End Time
Substrates Used		01.01.2008	31.12.2008
Electricity Production		01.01.2008	31.12.2008
Heat Utilisation		01.01.2008	31.12.2008
On-Site Inspection / Communication with the Biogas Plant Operator			
Fundamental Structure	28.05.2009		
Operational Mode	28.05.2009		
Temporary On-Site Measurements			
Parasitic Electric Energy	28.05.2009 06.07.2009		
Runtime of Each Component		16.10.2009	01.03.2010
Composition of Biogas	06.07.2009		
Methane Emissions	06.07.2009		
External Analysis			
Samples for Biochemical Analysis	16.10.2009		
Biochemical Analysis		17.10.2009	20.10.2009
Samples for Remaining Biogas Potential	10.02.2010		
Remaining Biogas Potential		12.02.2010	17.03.2010

		2009				
		Biogas Plant BY 8				
General						
Start of Operation	2004, Extension 2006					
Planning/Construction	NQ Anlagentechnik GmbH					
Farmland for Energy Crops	195 ha					
Livestock on Farm	0					
Substrate	[%]	[t/d]				
Maize Silage	74.3	19.1				
Grass Silage	22.6	5.8				
Sheep Manure	2.9	0.8				
Straw	0.1	0.04				
Total		**25.7**				
mean Dry Matter*						
[% DM]	33.4					
mean organic Dry Matter*						
[% oDM]	93.4					
Operating Data		Digester 1	Digester 2	Post-Digester	Residue Storage Tank	Total
Digestion Temperature	[°C]	44	44	**44**	**44**	
Active Digester Volume	[m^3]	900	1,200	1,500	1,200	4,800
Added Substrate Mass	[t/d]	13	13			26
Added Substrate Volume	[m^3/d]	23	23			46
Hydraulic Retention Time*	[d]	39	52	33	26	98
Volume Load	[kg $_{oDM}$/$m^3$$_{active\ digester}$·d]					1.7
Specific Digester Volume	[m^3/$kW_{el.\ capacity}$]					13
Biogas						
Composition	CH_4 [%]	CO_2 [%]	O_2 [%]	H_2S [ppm]	NH_3 [ppm]	
	53.6	44.3	0.3	6	80	
Methane Yield*	[Nm^3/t_{FM}]	89.4				
Methane Productivity*	[$Nm^3/m^3_{active\ digester}$]	0.5				
CHP-Unit						Total
Number		1	1			
Manufacturer		Hagl	Hagl			
Type		Gas	Gas			
Engine		MAN	MAN			
Cylinder		6	6			
Displacement	[l]	12.8	**12.8**			
El. Efficiency**	[%]	38.5	38.5			
Th. Efficiency**	[%]	43.0	43.0			
El. Capacity**	[kW_{el}]	190	190			380
Th. Capacity**	[kW_{th}]	212	212			424
Production of Electricity						Total
Mean Power Output	[kW_{el}]	184	184			369
CHP-Unit Utilisation	[%]	**97**	**97**			97
Theoretical CHP-Unit Utilisation	[h/a]	8,496	8,496			8,496
Gross Electricity Production	[kWh_{el}/a]	1,614,313	1,614,313			3,228,626
Electricity Production per t $_{FM}$	[kWh_{el}/t_{FM}]	344	344			344
Heat Utilisation						
Heat Output*	[kWh_{th}/a]	**3,602,467**				
Process Heat*	[kWh_{th}/a]	**450,308**				
Utilised Heat Quantity	[kWh_{th}/a]	**0**				
Total Efficiency	η_{total}					
	[%]	**44**				
Parasitic Electric Energy						
Biogas Production Electric Energy Consumption	[kWh_{el}/d]	**430.0**				
CHP-Unit Electric Energy Consumption	[kWh_{el}/d]	**204.9**				
Total	[kWh_{el}/d]	**634.9**				
Parasitic Electric Energy	[%]	**7.2**				
Specific Stirring Electric Energy Consumption	[kWh_{el}/t_{FM}]	**12.6**				
Specific Stirring Electric Energy Consumption	[kWh_{el}/100$m^3_{active\ digester}$]	**6.8**				
Feeding System Electric Energy Consumption without Slurry	[kWh_{el}/t_{FM}]	**0.4**				
Substrate Conversion Factor						
Factor	**[%]**	**86**				
*** calculated**						
**** according to manufacturer/datasheet**						



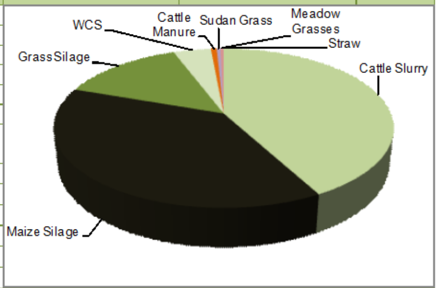
Biogas Plant BY 8			
Long-Term Data	Date	Start Time	End Time
Substrates Used		01.12.2008	30.06.2009
Electricity Production		01.12.2008	30.06.2009
Heat Utilisation	no utilisation		
On-Site Inspection / Communication with the Biogas Plant Operator			
Fundamental Structure	07.08.2009		
Operational Mode	07.08.2009		
Temporary On-Site Measurements			
Parasitic Electric Energy	27.05.2009 07.07.2009		
Runtime of Each Component	monitoring unit		
Composition of Biogas	27.05.2009		
Methane Emissions	27.05.2009		
External Analysis			
Samples for Biochemical Analysis	05.10.2009		
Biochemical Analysis		06.10.2009	09.10.2009
Samples for Remaining Biogas Potential	no measurement		
Remaining Biogas Potential	no measurement		

2009

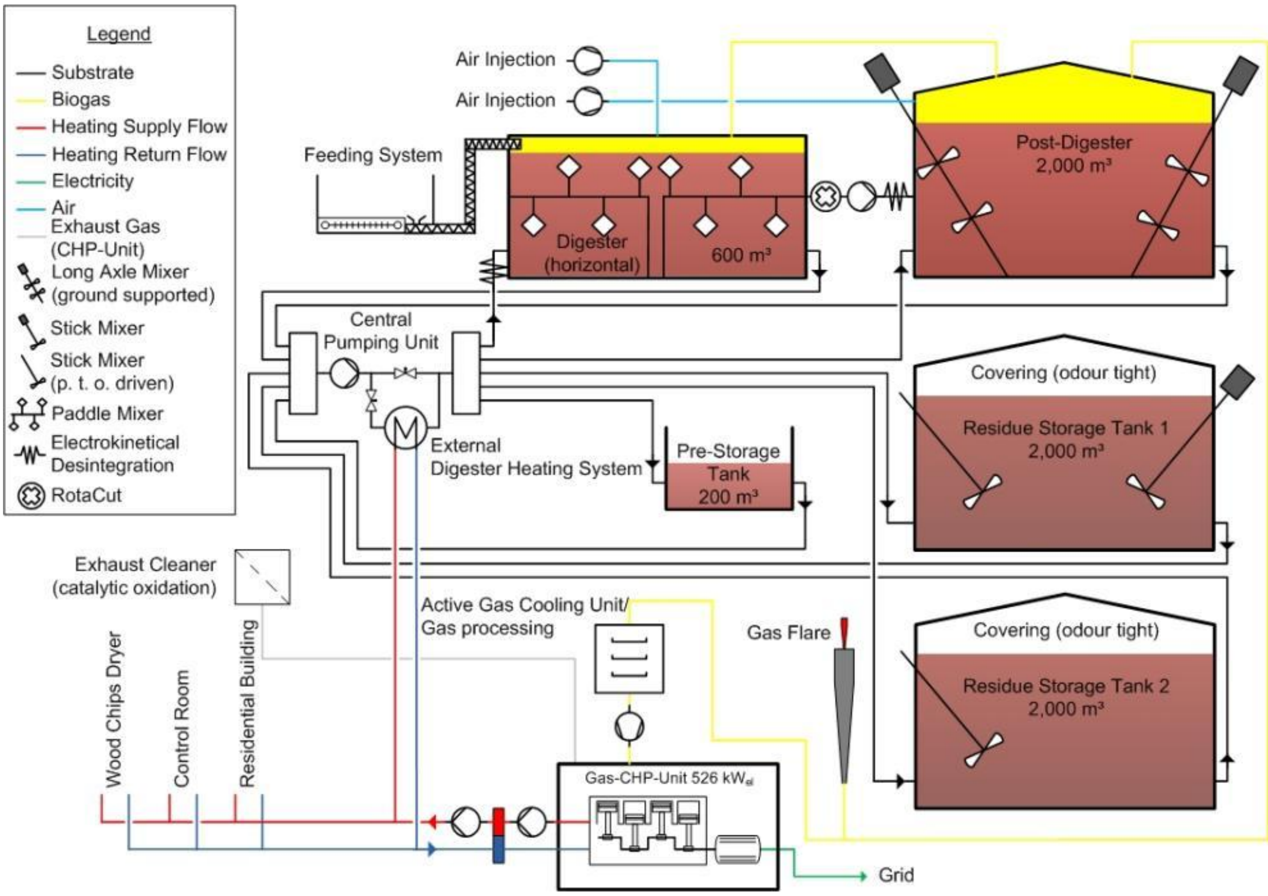
Biogas Plant BY 9

General						
Start of Operation	2006					
Planning/Construction	Cowatec GmbH					
Farmland for Energy Crops	200 ha					
Livestock on Farm	260 LU Feeder Cattle					

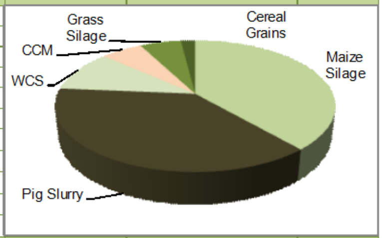
Substrate	[%]	[t/d]
Cattle Slurry	42.1	17.0
Maize Silage	38.3	**15.5**
Grass Silage	13.9	5.6
WCS	4.3	1.7
Cattle Manure	0.7	0.3
Sudan Grass	0.4	0.2
Meadow Grasses from Landscape Conservation	0.4	0.2
Straw	0.0	**0.0**
Total		**40.5**
mean Dry Matter*		
[% DM]	22.7	
mean organic Dry Matter*		
[% oDM]	91.5	



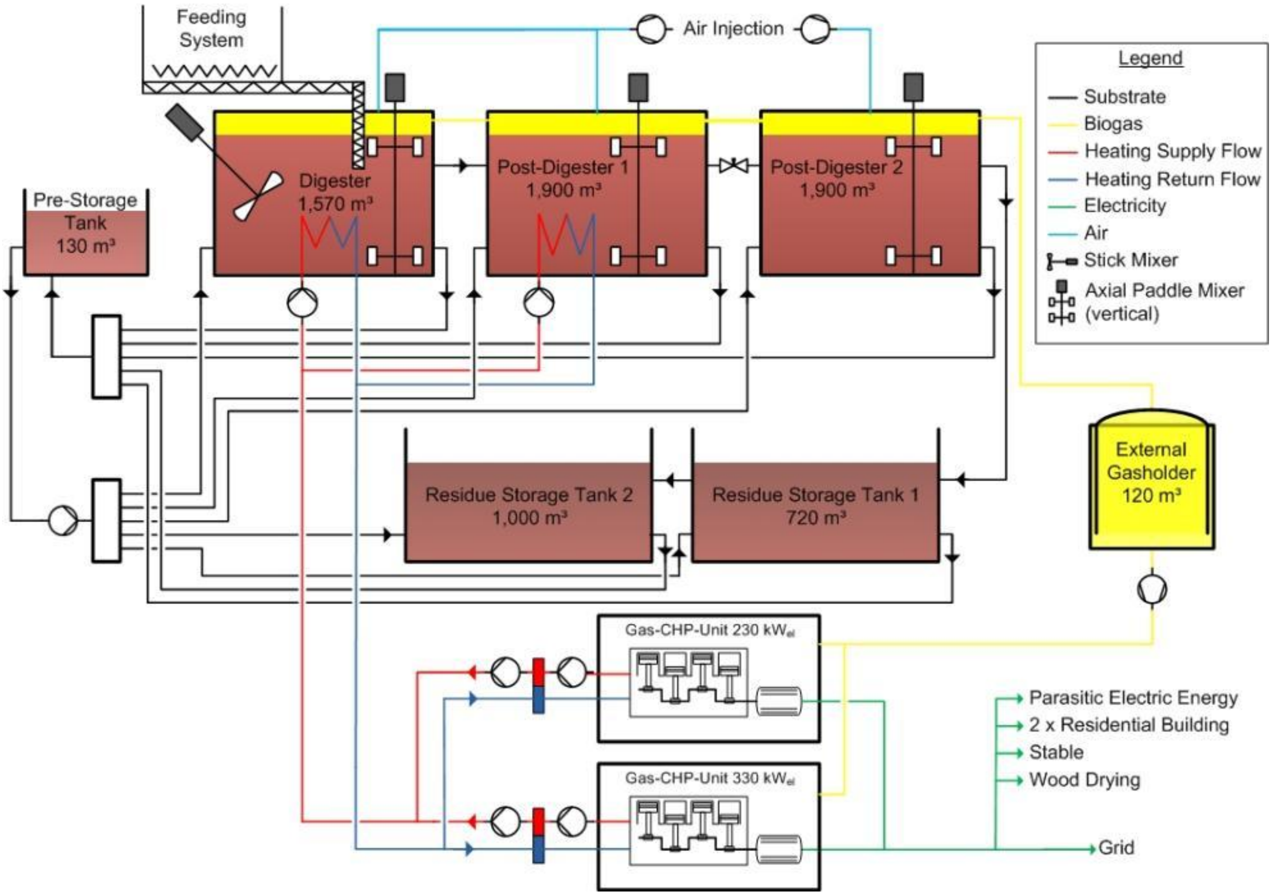
Operating Data		Digester	Post-Digester	Residue Storage Tank 1	Residue Storage Tank 2	Total
Digestion Temperature	[°C]	44	42	-	-	
Active Digester Volume	[m³]	600	2,000	2,000	2,000	2,600
Added Substrate Mass	[t/d]	40				40
Added Substrate Volume	[m³/d]	59				59
Hydraulic Retention Time*	[d]	10	34			44
Volume Load	[kg $_{oDM}$/m³$_{active\ digester}$·d]					3.2
Specific Digester Volume	[m³/kW$_{el.\ capacity}$]					5
Biogas						
Composition	CH_4 [%]	CO_2 [%]	O_2 [%]	H_2S [ppm]	NH_3 [ppm]	
	59.2	-	0.5	44	-	
Methane Yield*	[Nm³/t$_{FM}$]	74.0				
Methane Productivity*	[Nm³/m³$_{active\ digester}$]	1.2				
CHP-Unit						Total
Number		1				
Manufacturer		Jenbacher				
Type		Gas				
Engine		Jenbacher				
Cylinder		12				
Displacement	[l]	29.2				
El. Efficiency**	[%]	40.4				
Th. Efficiency**	[%]	43.5%				
El. Capacity**	[kW$_{el}$]	526				526
Th. Capacity**	[kW$_{th}$]	566				566
Production of Electricity						Total
Mean Power Output	[kW$_{el}$]	503				503
CHP-Unit Utilisation	[%]	**96**				96
Theoretical CHP-Unit Utilisation	[h/a]	8,385				8,385
Gross Electricity Production	[kWh$_{el}$/a]	4,410,300				4,410,300
Electricity Production per t $_{FM}$	[kWh$_{el}$/t$_{FM}$]	298				298
Heat Utilisation						
Heat Output*	[kWh$_{th}$/a]	**4,745,684**				
Process Heat	[kWh$_{th}$/a]	**329,558**				
Utilised Heat Quantity	[kWh$_{th}$/a]	**2,180,159**				
Total Efficiency	η_{total}					
	[%]	**62**				
Parasitic Electric Energy						
Biogas Production Electric Energy Consumption	[kWh$_{el}$/d]	**649.8**				
CHP-Unit Electric Energy Consumption	[kWh$_{el}$/d]	268.5				
Total	[kWh$_{el}$/d]	**918.3**				
Parasitic Electric Energy	[%]	7.6				
Specific Stirring Electric Energy Consumption	[kWh$_{el}$/t$_{FM}$]	**5.8**				
Specific Stirring Electric Energy Consumption	[kWh$_{el}$/100m³$_{active\ digester}$]	9.1				
Feeding System Electric Energy Consumption without Slurry	[kWh$_{el}$/t$_{FM}$]	**1.5**				
Substrate Conversion Factor						
Factor	**[%]**	**116**				
*** calculated**						
**** according to manufacturer/datasheet**						



Biogas Plant BY 9			
Long-Term Data	Date	Start Time	End Time
Substrates Used		01.01.2009	31.12.2009
Electricity Production		01.01.2009	31.12.2009
Heat Utilisation		01.01.2009	31.12.2009
On-Site Inspection / Communication with the Biogas Plant Operator			
Fundamental Structure	12.07.2010		
Operational Mode	12.07.2010		
Temporary On-Site Measurements			
Parasitic Electric Energy	13.07.2010 14.07.2010		
Runtime of Each Component		14.07.2010	04.08.2010
Composition of Biogas	14.07.2010		
Methane Emissions	12.07.2010		
External Analysis			
Samples for Biochemical Analysis	12.07.2010		
Biochemical Analysis		14.07.2010	16.07.2010
Samples for Remaining Biogas Potential	17.02.2010		
Remaining Biogas Potential		19.02.2010	24.03.2010



2009						
Biogas Plant BY 10						
General						
Start of Operation	2002					
Planning/Construction	Biogas Hochreiter GmbH					
Farmland for Energy Crops	250 ha					
Livestock on Farm	1500 Pigs					
Substrate	[%]	[t/d]				
Maize Silage	38.6	15.6				
Pig Slurry	37.8	**15.3**				
WCS	10.2	4.1				
CCM	5.8	2.3				
Grass Silage	5.7	2.3				
Cereal Grains	2.0	**0.8**				
Total		**40.4**				
mean Dry Matter*						
[% DM]	25.8					
mean organic Dry Matter*						
[% oDM]	93.9					
Operating Data		Digester	Post-Digester 1	Post-Digester 2	Residue Storage Tank	Total
Digestion Temperature	[°C]	51	47	**35**	-	
Active Digester Volume	[m³]	1,570	1,900	1,900	1,720	5,370
Added Substrate Mass	[t/d]	40				40
Added Substrate Volume	[m³/d]	54				54
Hydraulic Retention Time*	[d]	29	35	35		99
Volume Load	[kg $_{oDM}$/m³$_{active\ digester}$·d]					1.8
Specific Digester Volume	[m³/kW$_{el.\ capacity}$]					10
Biogas						
Composition	CH_4 [%]	CO_2 [%]	O_2 [%]	H_2S [ppm]	NH_3 [ppm]	
	51.5	46.3	2.0	98	75	
Methane Yield*	[Nm³/t$_{FM}$]	98.5				
Methane Productivity*	[Nm³/m³$_{active\ digester}$]	0.7				
CHP-Unit						Total
Number		1	1			
Manufacturer		Hochreiter	Hochreiter			
Type		Gas	Gas			
Engine		MAN	MAN			
Cylinder		12	12			
Displacement	[l]	21.93	**21.93**			
El. Efficiency**	[%]	33.3	33.3			
Th. Efficiency	[%]	-	-			
El. Capacity**	[kW$_{el}$]	330	230			560
Th. Capacity	[kW$_{th}$]	-	-			-
Production of Electricity						Total
Mean Power Output	[kW$_{el}$]	325	226			551
CHP-Unit Utilisation	[%]	**98**	**98**			98
Theoretical CHP-Unit Utilisation	[h/a]	8,622	8,622			8,622
Gross Electricity Production	[kWh$_{el}$/a]	2,845,133	1,982,972			4,828,105
Electricity Production per t $_{FM}$	[kWh$_{el}$/t$_{FM}$]	327				327
Heat Utilisation						
Heat Output* **	[kWh$_{th}$/a]	**6,764,175**				
Process Heat*	[kWh$_{th}$/a]	**845,522**				
Utilised Heat Quantity	[kWh$_{th}$/a]	**0**				
Total Efficiency	η_{total}					
	[%]	**39**				
Parasitic Electric Energy						
Biogas Production Electric Energy Consumption	[kWh$_{el}$/d]	**326.3**				
CHP-Unit Electric Energy Consumption	[kWh$_{el}$/d]	321.7				
Total	[kWh$_{el}$/d]	**648.0**				
Parasitic Electric Energy	[%]	4.9				
Specific Stirring Electric Energy Consumption	[kWh$_{el}$/t$_{FM}$]	**6.3**				
Specific Stirring Electric Energy Consumption	[kWh$_{el}$/100m³$_{active\ digester}$]	4.8				
Feeding System Electric Energy Consumption without Slurry	[kWh$_{el}$/t$_{FM}$]	**2.1**				
Substrate Conversion Factor						
Factor	**[%]**	**120**				
* calculated						
** according to manufacturer/datasheet						
*** assumption						



Biogas Plant BY 10			
Long-Term Data	Date	Start Time	End Time
Substrates Used		01.01.2009	31.12.2009
Electricity Production		01.01.2009	31.12.2009
Heat Utilisation	no utilisation		
On-Site Inspection / Communication with the Biogas Plant Operator			
Fundamental Structure	16.04.2010		
Operational Mode	16.04.2010		
Temporary On-Site Measurements			
Parasitic Electric Energy	19.05.2010		
Runtime of Each Component		19.05.2010	31.05.2010
Composition of Biogas	26.04.2010		
Methane Emissions	26.04.2010		
External Analysis			
Samples for Biochemical Analysis	26.04.2010 n.A.		
Biochemical Analysis		28.04.2010 25.05.2010	03.05.2010 27.05.2010
Samples for Remaining Biogas Potential	17.02.2010		
Remaining Biogas Potential		19.02.2010	24.03.2010

Appendix C:

Current Clamps Accuracy and Specifications

i430flex AC Current Clamps

Electrical Specifications	
Measuring range	30 to 3000 A ac
Maximum non destructive current	100 kA
Output signal	85 mV at 1000 A rms, 50 Hz
Basic accuracy	± 1% of reading at 25 °C, 50 Hz
Linearity	± 0.2 % of reading at 10 %...100 % of range
Noise	< 1 mV rms at 10 Hz…7 kHz
Additional errors:	
with temperature (0 to +70 °C)	0.08 % of reading /°C
with position of conductor in the probe window	± 2 % of reading (bus ≥ 2,5cm from coupling)
Phase shift 45 to 65 Hz	< ± 1 °
Bandwidth (-3dB)	10 Hz to 7 kHz

i200s AC Current Clamps

Electrical Specifications 20 A Range	
Measuring range	0.1 to 24 A ac
Maximum current	24 A
Crest factor	< 3
Maximum non-destructive current	200 A (Frequency ≤ 1 kHz and crest factor < 3)
Output signal	100 mV/A
Output impedance	≤ 20 Ω at 1 kHz
Basic accuracy	
48 Hz to 65 Hz	< 2 % + 0.5 A
Additional errors:	
40 Hz to 48 Hz and 65 Hz to 1 kHz	+ < 10 %
1 kHz to 10 kHz	+ < 15 %
Phase shift	unspecified

Electrical Specifications 200 A Range	
Measuring range	0.5 to 240 A ac
Maximum current	240 A
Crest factor	< 3
Maximum non-destructive current	at Frequency ≤ 1 kHz and crest factor < 3
Continuous	200 A
10 min ON / 30 min OFF	240 A
Output signal	10 mV/A
Output impedance	≤ 10 Ω at 1 kHz
Basic accuracy	
48 Hz to 65 Hz	
0.5 A to 10 A	≤ 3.5% + 0.5 A
10 A to 40 A	< 3% + 0.5 A
40 A to 100 A	< 2.5% + 0.5 A
100 A to 240 A	≤ 1.5% + 0.5 A
Additional errors:	
40 Hz to 48 Hz and 65 Hz to 1 kHz	+ < 3 %
1 kHz to 10 kHz	+ < 12 %
Phase shift	
0.5 A to 10 A	Unspecified
10 A to 40 A	≤ 6 °
40 A to 100 A	≤ 4 °
100 A to 240 A	≤ 3 °

Appendix D:

Publications

HÄRING, G.; SONNLEITNER, M.; TRINKL, C.; ZÖRNER, W. (2010) Ökologische und ökonomische Optimierung von bestehenden und zukünftigen Biogasanlagen – Erste Projektergebnisse. In: *19. Jahrestagung Fachverband Biogas e.V., Leipzig, 02.-04.02.2010*. Freising: Fachverband Biogas e.V., p. 166.

HÄRING, G.; SONNLEITNER, M.; ZÖRNER, W.; BRÜGGING, E.; BÜCKER, C.; VOGT, R. und WETTER, C. (2010) Ökologische und ökonomische Optimierung von bestehenden und zukünftigen Biogasanlagen – Projektergebnisse. In: *19. Symposium Bioenergie, Bad Staffelstein, 25.-26.11.2010.* Regensburg: Ostbayerisches Technologie-Transfer-Institut e.V. (OTTI), pp. 289-294.

HÄRING, G.; SONNLEITNER, M.; ZÖRNER, W.; BRÜGGING, E.; BÜCKER, C.; VOGT, R. und WETTER, C. (2011) Ökologische und ökonomische Optimierung von bestehenden und zukünftigen Biogasanlagen – Projektergebnisse. In: *20. Jahrestagung Fachverband Biogas, Nuremberg, 11.-13.01.2011.* Freising: Fachverband Biogas e.V., pp. 137-147.

HANBY, V.; HÄRING, G.; SONNLEITNER, M.; ZÖRNER, W. (2011) Ecological and Economic Optimisation of Biogas Plants. In: *17th International Conference for Renewable Resources and Plant Biotechnology, Poznan (Poland), 30.-31.05.2011*. Magdeburg: PPM Pilot Pflanzenöltechnologie Magdeburg e.V..